STUDY OF AIRCRAFT IN SHORT HAUL TRANSPORTATION SYSTEMS

FINAL REPORT

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THE MISSION ANALYSIS DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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PREFACE

The prime responsibility for this study was placed in the Commercial Airplane Division of The Boeing Company.

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1.0 INTRODUCTION

This report presents the results of a study conducted by The Boeing Company under contract to the Mission Analysis Division, Office of Advanced Research and Technology, National Aeronautics and Space Administration. The study was conducted principally by the Commercial Airplane Division at Renton, with rotorcraft technology and engineering being supplied by the Vertol Division at Morton, Pennsylvania.

The intent of this study is to evaluate short-haul transport aircraft, of a more advanced technology than has been assumed in other studies, in operation in several assumed transportation systems in the 1985 time period. The systems are limited to intercity operation, and the intracity use of any of these designs is not considered in this study. Thus this study is not concerned with markets where city-pair trip distance is less than 30 miles. In the study, various advanced conceptual aircraft, ranging from vertical takeoff and landing (VTOL) through short takeoff and landing (STOL) to conventional takeoff and landing (CTOL) types, are assessed for their relative suitability to perform short-haul transport missions.

The analysis was conducted in two phases. Phase I was concerned with preparation of various conceptual aircraft configurations and the study of their operation on a number of assumed transportation systems. The intent in Phase II was then to select for detailed analysis three representative systems and the optimum aircraft concepts from each of these systems.

The report is prepared in two volumes. Volume I contains the objectives of the study, study constraints, summary, conclusions, and discussions and recommendations. Also included are sections detailing the advanced technology assumed for 1985, and the determination and selection of the configurations. Volume 2 contains the detailed sections on market analysis, vehicle and systems economics, and an analysis of the vehicles when applied to the transportation systems.

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2.0 OBJECTIVES

The principal objectives of this study are to:

- Determine the relative suitability of various advanced conceptual aircraft to perform short-haul missions in the 1980's, including the effects of realistic route structures and system operations
- Determine the sensitivity of mission performance to changes in aircraft characteristics and system operations
- Identify key problem areas in which additional research may result in significant improvement in aircraft transportation systems

To ensure that the results of such an investigation are worthwhile, as broad a transportation requirement as possible is considered, with the systems model depicted as nearly representative of the time period specified as presently possible. Consequently, three separate areas of the country are studied, two of whose transportation characteristics — density of demand and length of trip segment — are significantly different. The areas studied are Northeast, West Coast, and Gulf Coast and Florida.

To assess the relative suitability of the concepts, various figures of merit are considered. In addition to the usual direct operating cost (DOC) versus range figure, vehicle profitability on a systems-wide basis is estimated. This introduces revenue passenger demand and aircraft fleet size aspects into the comparison procedure. The extent and magnitude of the noise generated by each concept are also used as a basis of comparison.

Of equal importance as an objective of the study is to review the many possible options of aircraft concept and fleet mix, and to assess the effect of design and operational variables on the conclusions of the study so that the most fruitful research areas may be identified as influenced by the most suitable concepts.

3.0 STUDY CONSTRAINTS AND GUIDELINES

Of prime importance in a study that involves any appreciable amount of systems analysis is a clear statement of the assumptions and limitations associated with the study. This is especially significant if the investigation concerns a possible transportation system beyond the near future.

This section of the report presents a series of qualifying statements, which are definitely aspects of the total short-haul transportation system problem and which need consideration and resolution before a practical system is evolved in the 1985 time period. It is considered unnecessary, however, and even in some instances impossible at this time to resolve these issues to satisfy the immediate objectives of this study for NASA.

By definition the study considers the 1985 time period, and investigates the relative suitability of the various VTOL/STOL/CTOL concepts. Thus, the question of whether in fact VTOL or STOL service would exist in significant quantity is not considered. It is assumed it will and that all of the concepts will be possible; hence the emphasis is to evaluate the suitability of the concepts and determine the research required.

While predictions on market size and technology are made for use in the systems model for the time period required, no attempt is made to address the question of how, in detail, that market growth will be stimulated between 1967 and 1985. Research has shown, however, that when transportation markets are stimulated by convenient, frequent service at competitive fares, they grow considerably. Thus, market size is estimated on the basis that the proposed V/STOL systems would, in fact, do this. Likewise, no investigation into a planned program of introduction of various V/STOL concepts into service between 1967 and 1985 is made, nor how such a program may affect the study results. It is recognized that there are different amounts of time, effort, and money implicit in each of the levels of technology specified for the various concepts, but no attempt has been made to base these levels on a specified program of events between 1967 and 1985. It should be emphasized, however, that the size of the market and the availability of both the concept and the relative level of technology do assume that both of these factors will be addressed and solutions found, and that an evolution to the levels assumed will actually be made.

Where it is believed that certain concepts will exist in 1985 by virtue of their existence in 1967 or of their first-generation introduction sometime later, then solutions for 1985 have been provided for these particular concepts whether they emerge in this study as most suitable or not.

One of the guidelines of the study is to establish the assumed transportation systems to include at least ten leading cities in the Northeastern United States, West Coast, and Gulf Coast and Florida regions. Consequently, the postulated markets are representative only of the systems model prepared for this study and are not intended as a company forecast of traffic levels from which sales forecasts could be made. While the detailed nature of the growth of these cities is not studied, it is assumed that the growth will still leave the major population or traffic-generating centers as discrete areas greater than approximately 80 miles apart. This is particularly significant in the Northeast states.

The study assumes that this V/STOL transportation service is supplied by one or two operators and does not consider the problem of possible government legislation of city service among several operators as typified by current CAB route-granting procedures. These operators are assumed to provide their services in an environment that is subsidized neither by government support nor by revenue from another part of a large transportation system. Thus, the cost of the ground facilities (but not the land) is included in the operating cost estimates. Sensitivity studies, however, do show the effect of omitting this cost.

The depth to which the economic analysis is pursued is limited because the postulated operators do not have an economic or financial history from which to work. Return on sales (ROS) has been selected as the profitability criterion because it is easily understood, widely accepted, and not overly sensitive to fare changes. Among the criteria not chosen is return on investment (ROI) because of its oversensitivity to fare changes and investment level and because of its time-sensitive nature, which makes the determination of ROI for a simple study point (1985) less valid than the determination of ROS. Passenger and operator preferences that can affect the estimates of market demand and operating cost are acknowledged to exist, but no attempt is made in this study to quantify these items when making market and cost estimates.

At the direction of NASA, no analysis is attempted of projected high-speed ground transportation systems or of their effects on the study results. Similarly, little emphasis is placed on making comparisons of operating costs, travel times, or costs of other competitive ground transportation systems.

While some technical details are specified by NASA in the contract guidelines and constraints, it is not generally intended that this study should involve any detailed analysis of specific technical areas, for example, noise, vehicle handling qualities, or particular problems associated with any one of the propulsion concepts. Rather, the study should provide visibility on a system-wide basis to the effect of gross level changes in design or operations technology.

It is recognized that different degrees of schedule reliability may exist due to differences in vehicle reliability as a function of the degree of complexity in vehicle design. In this study, it is assumed that all concepts are equally reliable and that the resulting levels of technology and development required in each concept will be the goal that must be achieved in order to provide this system. In this way the degree of development required is a figure of merit for concept comparison.

4.0 CONCLUSIONS AND DISCUSSION

4.1 Conclusions

The economic suitability to perform short-haul missions in the 1980's of most of the V/STOL concepts studied is demonstrated by their ability to make a profit when in competition with conventional airplane (CTOL) systems, if the V/STOL air fare structure allows for a premium charge, the increment being equivalent to the difference in terminal access costs (thereby causing the total trip costs by any mode to be equal).

The relative economic suitability between concepts is, however, more difficult to define precisely in view of the close proximity of the levels of total system profit of some of the concepts when exercised with the design assumptions as determined for use in this study. While these assumptions are established as being a sound basis upon which to compare many concepts, and hence the solutions presented represent a highly probable conclusion, it is recognized that these assumptions are subject to change, in total or as applied to only certain concepts. The configuration parameters are difficult to define for this advanced period where certification requirements, as yet undefined, may have significant effects on airplane characteristics. Particular effort has been made to evaluate what these influences may be, and trade studies are included that cover most of these possibilities. In sec. 6.6.1 of this volume can be seen, for example, the effect on system profit of applying different assumptions of vehicle operation and of cost estimation. It is possible, therefore, to establish many solutions to the problem of selecting the most suitable concept from an economic viewpoint. Consequently, it is concluded that, at this time, economic suitability does not provide a satisfactory measure with which to segregate precisely the potential short haul vehicle concepts.

It is shown that groups of concepts and operating environments are more readily identifiable, where concepts within these groups exhibit very similar profit potential. These groups can then provide a broad measure of relative economic suitability. The groups can be classified as follows. A "downtown" group of nonrotor concepts comprising the jet lift and fan-in-wing VTOL concepts and the high lift and high acceleration STOL concepts of under 1700 ft (518 m) design field length; a "downtown" rotor group, comprising the tilt wing and the folding tilt rotor VTOL concepts; a pure helicopter as separate from the rotor VTOL concepts; a "suburb" STOL high lift concept of approximately 2200-ft (671 m) design field length; and finally two groups of conventional CTOL aircraft representing expedited or low maneuver time operations and congested or normal maneuver time operations.

These groups are found to exhibit trends that are discernibly different from each other such that it is possible to note that the rotor VTOL concepts (exclusive of the helicopter) are more economical at the shorter ranges, while the non-rotor VTOL concepts are better at relatively larger distances. Aircraft size and the differences in fare in the various geographical regions make it impossible to quote a distinct demarcation line in range. The short field (less than 1700 ft) or downtown STOL concepts are included in the non-rotor group. The 2200-ft high lift STOL concept, however, is found to be the most economical V/STOL concept at the longer ranges.

If, however, the operator of the V/STOL system finds that the competitive situation does not allow a premium fare to be charged, and if it is postulated that the air fare of the V/STOL system may be equal to the CTOL fare, then the above statements must be modified.

This modification throws doubt on the economic suitability of some of the concepts. Their relative suitability however, does not substantially change. The most noticeable effect is the decline in profitability of the V/STOL concepts when compared with the CTOL concepts, which is to be expected.

Thus, while the economic suitability between the concepts is difficult to define precisely at this time, and hence makes the selection of a best concept almost impossible on the basis of profit potential, the relative suitability from the aspect of noise may be easier to distinguish. Noise may in fact be the major criterion upon which an ultimate selection of a suitable concept or concepts is made. It is shown that generally the noise level of rotor vehicles is some 10 to 17 PNdB lower than that of nonrotor downtown vehicles. However, the critical factor to be considered here is that there does not exist at this time a comprehensive set of acceptance criteria against which the noise aspects of vehicles can be measured. Thus, until these criteria are established it is not possible to determine that some concepts are acceptable while others are not, even though it is possible to show some are quieter than others and hence are potentially more suitable.

Therefore, consideration of suitability from the economic viewpoint generally favors the V/STOL concepts as a group. But if it is implied that this V/STOL system is operated from a downtown or center of a traffic-generating area, the final determination of overall suitability of any particular concept will have to await the establishment of noise acceptance criteria and the results of further research into noise suppression where the criteria indicate the need.

This does not mean that there are other criteria for measuring suit ability, for example vibration and acceleration. But it does recognize the primary importance of the economic suitability within an environment tolerated by the community.

Areas of research are established that are generally necessary for this potentially profitable situation to exist, in addition to certain specific areas associated with certain concepts. The importance of developing acceptance criteria and continuing research into noise suppression generally has been emphasized. Otherwise, however, no attempt has been made to select an order of preference for any particular area of research associated with any specific concept where such selection might be interpreted as being based on the concept's suitability to perform short-haul missions. Further, it is concluded that future research on a broad field encompassing all possible concepts is still necessary to provide a firmer base from which to prepare a more precise concept comparison.

While it is shown that certain rotor VTOL concepts are indeed less noisy and more profitable at some ranges than nonrotor VTOL concepts, it is recognized that the principal difference in profitability is in the apparently lower lift system maintenance costs associated with rotor concepts. Considering that the assumption of equal system reliability is made at this time, it should be recognized that more time and money will probably be spent to achieve this level in the relatively more complex rotor systems than in the lift engine or the lift fan systems. While this conclusion can of itself be regarded as a goal for research, it is not certain this far ahead of time (1985) that the goal will be reached or that it would not be more cost-effective to concentrate the contemplated money and work into developing a system that is possibly more reliable.

Throughout this study it is assumed that the V/STOL systems exist in competition with the CTOL system. In fact, the CTOL concepts are used to establish a base fare level to represent the air competition that V/STOL systems must recognize. Thus again, while the study shows that certain V/STOL concepts can be profitable in competition with these CTOL systems, it must also be recognized that the development required in the CTOL system is far less than in certain VTOL concepts.

It is concluded that certain areas of research are essential to enhance the possibility that certain V/STOL concepts can offer a practical and profitable service in short-haul intercity transportation that is acceptable to the community. It is also concluded, therefore, that if the apparent suitability advantage of specific concepts is also to be realized, then the expenditure of more effort and money is implicit in analyzing and achieving this advantage than would be necessary in other less complex systems. In addition, unless emphasis is placed on the establishment of acceptance criteria and unless research noise suppression is continued, it is possible that an economically suitable system may not, in fact, be a system that is acceptable to the community.

Further consideration must still be given to the possibility that a rapid transit system to a suburban STOL port or the conventional CTOL airport can provide a service that is just as convenient and inexpensive and even less disturbing to the community than a downtown V/STOL port for intercity service.

In view of these possibilities, a penetrating review must be made to decide whether the specific V/STOL system research is justifiable for a commercial transportation system.

4.2 Discussion

Earlier it is stated that the profitability difference between certain concepts is at this time small and uncertain. Aside from the possible existence of assumptions different from those established for the base level of this study, which may allow a clearer segregation of concepts, the small profit difference is assessed as follows. A detailed study of the analysis. and in particular the direct operating costs, shows that apart from small differences due to airplane size and fuel quantity burned, the major difference is lift system maintenance. The difference appears to emanate from the fact that any lift system that uses gas generators in addition to cruise engines, with the associated penalties of relatively high first price and costly overhaul and maintenance, will experience higher direct operating costs. This corollary is based on the assumption that all systems are assumed to have equal reliability. If this is not true, then the relative level of operating costs between VTOL concepts could change.

Thus, until some practical operating experience has been obtained with each of the various lift systems studied, it will be difficult to assess the true relative operating costs. Engineering judgment and past experience can certainly indicate the concept that is likely to need the most development to establish a profitable level of reliability. But the precise determination of these levels is beyond the scope of this study.

A further factor affecting the relative suitability of concepts is V/STOL fare levels. It is shown how the level of operator profit varies when a premium fare is charged by the V/STOL operator. This fare is the same fare the conventional airplane operator charges plus an increment to allow for the difference in access costs between the V or STOL port and the CTOL airport (so that the total trip cost by any mode is the same). This assumption gives one measure of concept relative suitability. If the V/STOL fare is made equal to the CTOL fare, however, it is apparent that a different suitability index is generated for each concept, and in fact some become unprofitable. Conversely, it is also shown that if an even higher premium is charged by the V/STOL operator, on the assumption that the passenger values the time that he saves by going by V/STOL, it is possible to form a clearer concept of the relative suitability margin because the time advantage of some of the concepts is now emphasized.

The extent to which the advances in technology in each of the disciplines is necessary to achieve these variously attractive systems is shown in the summary. For instance (see fig. 62), all concepts gained in an economic sense from the advance in structural materials that is postulated, and this gain appears to be one of the strongest forces contributing to the reduction of operating costs. All concepts reflect the advances assumed for the various lift systems and augmented power systems in three areas: (1) increased usable life, (2) increased reliability, and (3) increased times between overhaul. It should be recognized that along with the assumption of advanced material properties goes another that considers that sufficient raw material is produced so that costs of the advanced materials are comparable to current aluminum and titanium and that manufacturing methods and cost are at least comparable to the 1966 level. The relative merits of research in other areas are also indicated. However, it should be realized that these indications do not provide any measure of how easy it will be to achieve the required levels of technology. It is possible that the advances postulated in the aerodynamic and propulsion areas are technically simpler and less costly to achieve than those in the advanced materials area.

High on the list of required research, but difficult to further quantify, is noise suppression at the source for all the V/STOL concepts if they are to operate freely from downtown sites. It is concluded that in some of the larger cities studied, although the V/STOL terminal site is determined and the need on one hand to place it in an area of low response to high noise levels and on the other hand to make it convenient to the traffic generating centers is recognized, it still may not be possible with some concepts to contain or limit noise levels to those considered acceptable. The rotor concepts do exhibit the lowest level, while the nonrotor concepts are higher by as much as another 10 PNdB. Costly vertical climbing maneuvers do assist in limiting noise in the general area but do little to lower it in the immediate vicinity of the terminals.

5.0 RECOMMENDATIONS

As a result of this study, key problem areas are identified in which additional research will enhance the possibility of an acceptable, efficient, and competitive short-haul air transportation system. Certain of the research areas will benefit all concepts, while others pertain to specific concepts.

However, in addition to recommending areas of research, it is evident from this study that in order to understand, and accordingly respond to, this total short-haul transportation system problem of the future and its development needs (whether research or stimulation) much more detailed study is required in various related areas. These areas, while not necessarily the responsibility of NASA, are presented here, as it is strongly believed that areas of research should not be recommended without the relevant support qualifications also being stated. In this current study assumptions have been made in the following very influential areas, and thus form qualifications to the research recommendations.

- The need for the system and its potential added convenience is assumed to have been justified.
- The traffic growth to the level specified in 1985 is assumed to have occurred gradually over the intervening period, having been stimulated by the provision of some next-generation convenient, economical, short-haul system (either VTOL, STOL, or even modified CTOL operation). The nature or timing of this next generation system is not analyzed in this current study.
- It is assumed that government agencies at the federal, state, and city level have planned for the existence of systems similar to those studied under this contract.
- It is assumed that competition from high-speed ground systems is not severe enough to preclude the possibility of a successful VTOL/STOL/CTOL short-haul air system.

Consequently, recommendations for research and further study include the necessity for work in studying the above areas before large commitments of time and money are made in certain technical research fields. These research efforts may further a system that may not prosper for reasons found in some of the above areas, even though it possesses the potential to operate fast, economical, and attractive vehicles.

In view of the difficulty in establishing clearly the suitability of any particular concept, no priorities have been assigned to the specific research efforts required by specific concepts. However, areas of research and further study are identified and broadly ordered that are critical to the implementation or improvement of an economical, successful short-haul system involving any of the V/S/CTOL concepts.

5.1 Areas of Research and Further Study

Technology

1. - Development of acceptance criteria for noise analysis
   - Noise suppression and effect of noise on population centers

2. - Develop design standards for V/STOL aircraft:

     Maneuver margins

     Stall margins

     Engine-out conditions and other conditions to be considered concurrently

     Design field length factor

     Control response requirements

     Handling characteristics

     Allowable horizontal deceleration and aircraft attitude limits for passengers
   - Landing aid and navigation systems (optimum for maximum airspace utilization)
   - Maximum runway acceptance rate (airplane/electronics integration)
   - Automatic landing systems 100% all weather
   - Air traffic control development

     } Improvement in air maneuver and ground maneuver times and en route block speeds, elimination of delays
   - Air traffic control and instrument displays for tight turn procedures in takeoff and landing
   - Reliability, maintainability

3. - Control system types, fly-by-wire, etc.
   - Translational command versus attitude command
   - Use of throttlable gas generators for hover control system
   - Human factor review of pilot tasks and display requirements

4. - Power plant integration/propulsion system reingestion
   - Stability and control aspects of aero/propulsive force interaction (configuration problem)

5. - Advanced structural materials
   - Gust alleviation, ride improvement
   - High lift (with and without propulsion power assist)
   - Propulsive lift versus aerodynamic lift
   - Terminal pad surface material

6. Specific to certain concepts:
   - Thrust deflection of bypass engines
   - Convertible fan engines
   - Increased life/cycle lift engines
   - Development time and cost of concepts and propulsion systems

5.2 Areas of Research and Further Study— Market/Vehicle Economics

<u>General</u>

1. - Traffic stimulants in short-haul market
   - Market penetration factors (specifically short haul)
   - Effect of convenience, passenger preference
2. - Geopolitical implications of city operation
   - Government influence
   - Future plans for terminal access and city connection
3. - Type of operator and operation
   - Pros and cons of multimode terminal location
   - Effect of high speed ground transportation

<u>Specific</u>

1. - Passenger travel habits and motivation in specific markets
   - Origin and destination data, city-pair data
   - Timing and growth of specific markets
2. - Competitive systems analysis
   - Cost and time of surface access to airport terminal
3. - Terminal design
   - Maintenance costs of various lift systems
   - Financial return to industry, manufacturer to develop a V/STOL system

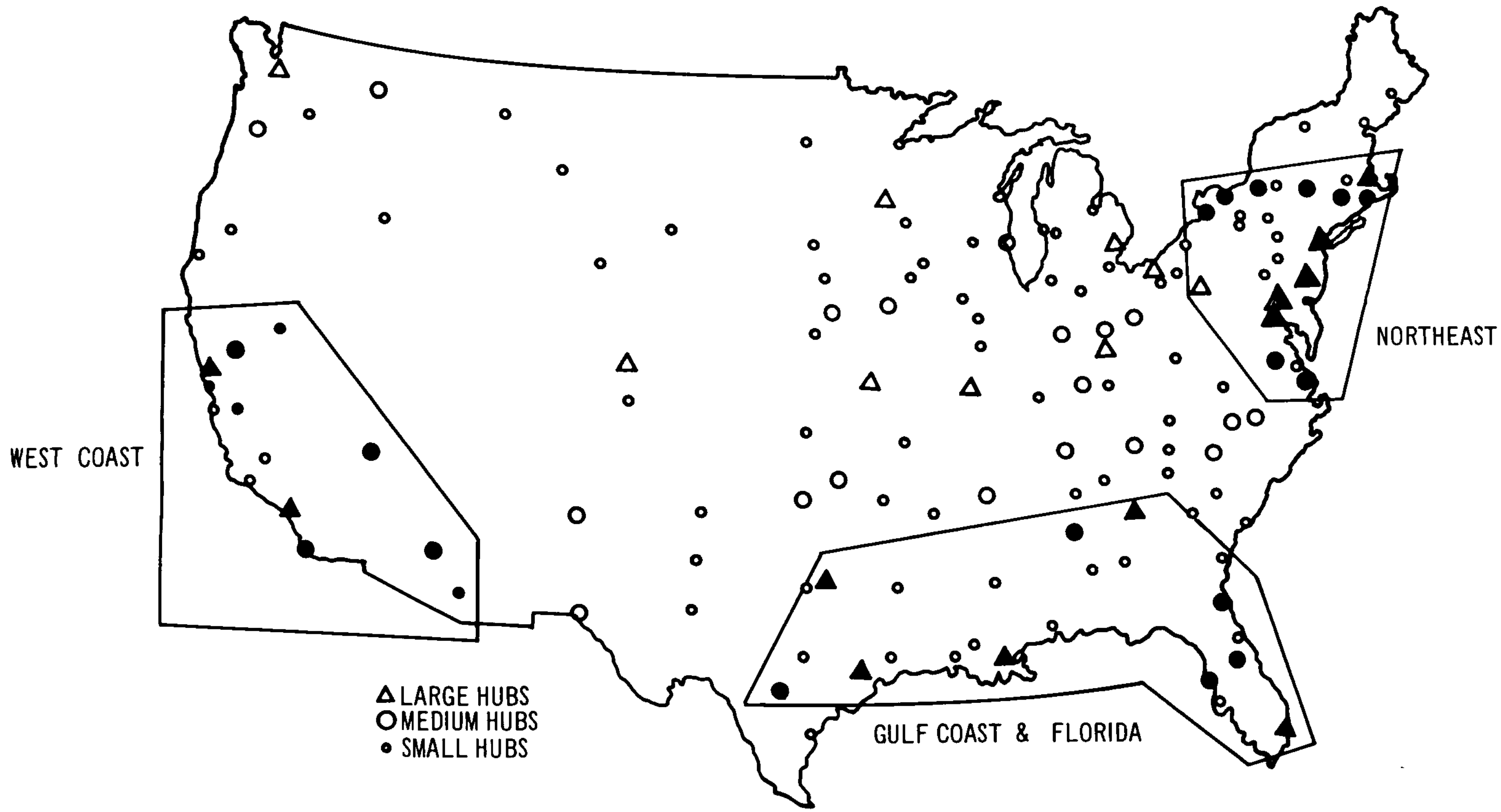


Figure 1: Selected Cities in Each Transportation System

6.0 SUMMARY OF RESULTS

A summary of the results of the major areas of the study are presented in this section. Expansion of each of these subjects is to be found in the corresponding sections of the main body of the report.

6.1 Study Transportation Systems

Three intercity transportation systems postulated for this study are shown in fig. 1. They are systems that link at least the ten leading cities in each region.

At most city locations the size of the traffic flow postulated for the 1985 period requires only one terminal, either VTOL or STOL, and this is considered as located in the best relevant area according to the definition of the concept "downtown" or "suburb."

In the larger cities (only 5 of the 33 studied) where more than one terminal is required because of either density of traffic or convenience of service, the suggested locations are chosen to represent the best compromise between convenience, disturbance to the community, and access to other transportation systems.

Estimates are made of total potential traffic flow for the V/STOL system in 1985 for various fare levels where elasticity of demand factors are included that recognize the influence of gross national product, average airline yield, average speed, and number of departures on demand. The base level for the V/STOL system reflects a market size that is approximately 25% larger than it would be if the effect of penetration of the surface transportation market because of the additional service offered had not been included. A higher level of traffic (an additional 40% larger), implying considerably more penetration, was also established where the additional convenience of this V/STOL service also was recognized. This latter level is presented only as part of a sensitivity study of market size, because considerably further analysis is required to substantiate the specific reaction of the market to this additional convenience. It is shown, however, that the absolute size of the market does not significantly change the conclusions concerning the principal objectives of the study.

A minimum level of service is postulated between each of the various sizes of city and between each of the specific locations of the terminals in the multi-terminal cities. This level is considered to be representative of an economically viable system. Generally if the predicted traffic does not support the minimum frequencies (10 departures per day) at 60% load factor in a 120-passenger aircraft, then that particular city-pair link is not considered part of the system.

The distribution of traffic flow between cities for various city-pair distances in each region is plotted in figs. 2 through 4. In the Northeast region several city-pairs are grouped in certain range categories for ease of illustration. The distinctive characteristics of traffic demand within each region are readily apparent from these figures.

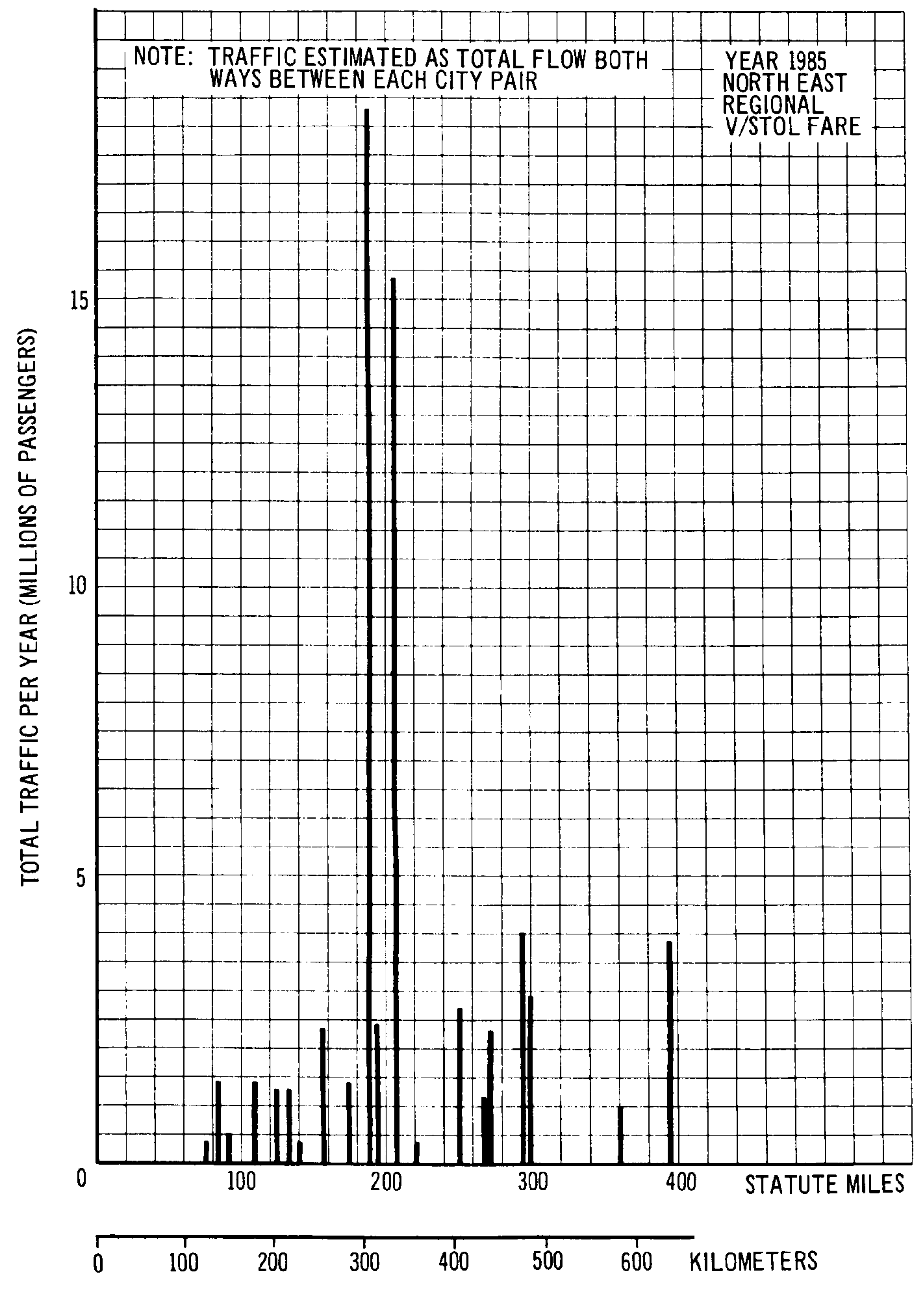


Figure 2: Total City-Pair Traffic Northeast—1985

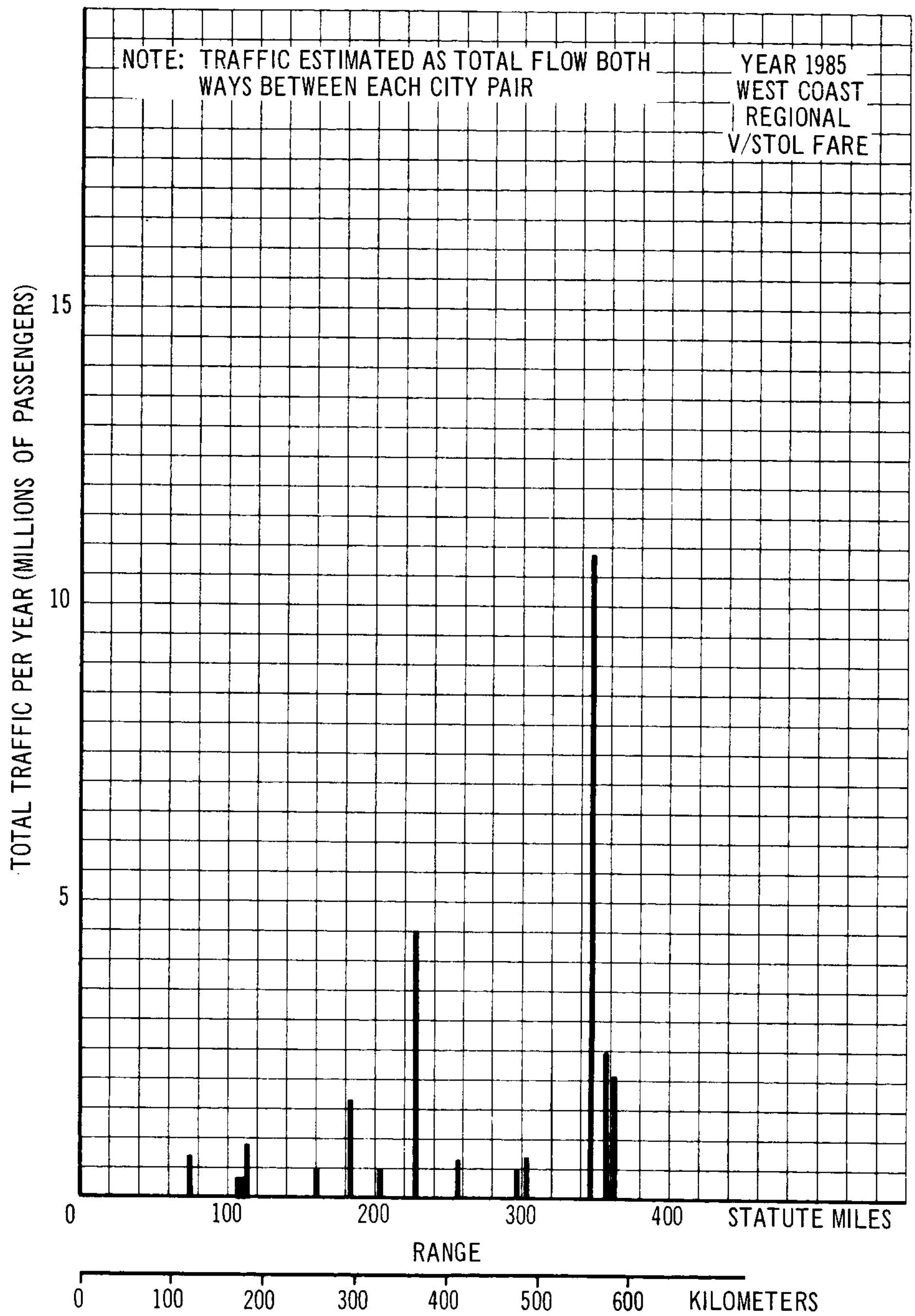


Figure 3: Total City-Pair Traffic West Coast—1985

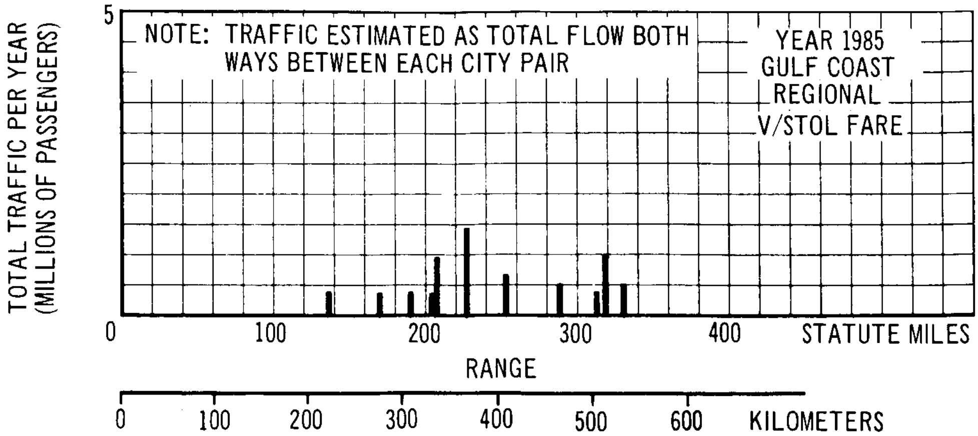


Figure 4: Total City-Pair Traffic Gulf Coast—1985

6.2 Advanced Technology

Prior to determining the principal design characteristics of the various vehicles, levels of technology in the various design and operational areas were established that are consistent with the study requirement of consideration of the transportation system in the year 1985.

Generally, from the detailed reviews in the respective areas, the following major improvements from current levels are postulated:

- Profile drag reduced by 10%.
- Drag divergence Mach number increased by 10%.
- Allowable placard speed increased by 20% for same comfort level.
- Usable lift coefficient for STOL approach increased more than 100%.
- Rotor aircraft lift-to-drag ratio increased approximately 100%.
- Powerplant weights reduced by 30% to 50%.
- Structure weights reduced by 30% to 36%.
- Equipment weights reduced by approximately 15% to 30%.
- Reduction in level of perceived noise from rotors of 10 PNdB and reduction from lift and cruise engines as much as 15 PNdB.
- Increase in avionic equipment reliability approximately 2000-fold.
- Reduction in volume of avionic equipment to approximately 1/100th.
- The possibility of substantially reduced air maneuver times occasioned by advanced displays and use of computer techniques in air traffic control procedures.
- Increase in reliability, usable life, and time between overhaul of lift system components.

NOTE: No fuel consumption improvement is postulated.

6.3 Study Concepts and Configurations

Nine different concepts involving twelve different configurations are analyzed in this study, displaying various VTOL, STOL, and CTOL capabilities (figs. 5 through 12).

During the preliminary phases of the study various design factors were exercised, and the aircraft summarized here represent the designs of each concept that best match the postulated transportation system requirements.

Throughout this study the terms "downtown" and "suburb" when applied to designs are generally to imply the following capabilities. "Downtown" indicates the ability to operate from the center of traffic generating areas or downtown areas, where the terminal dimensions are a maximum of 1700 by 600 ft; whereas "suburb" indicates the ability to operate from a terminal geographically located somewhere between the center of the traffic generating area and the conventional airport, which is generally an appreciable distance from the center of the community. The suburb terminal dimensions are considered to be approximately 2200 by 600 ft. Finally, the term CTOL is applied to an aircraft that makes conventional takeoff and landing approaches into a field at least 6000 ft long.

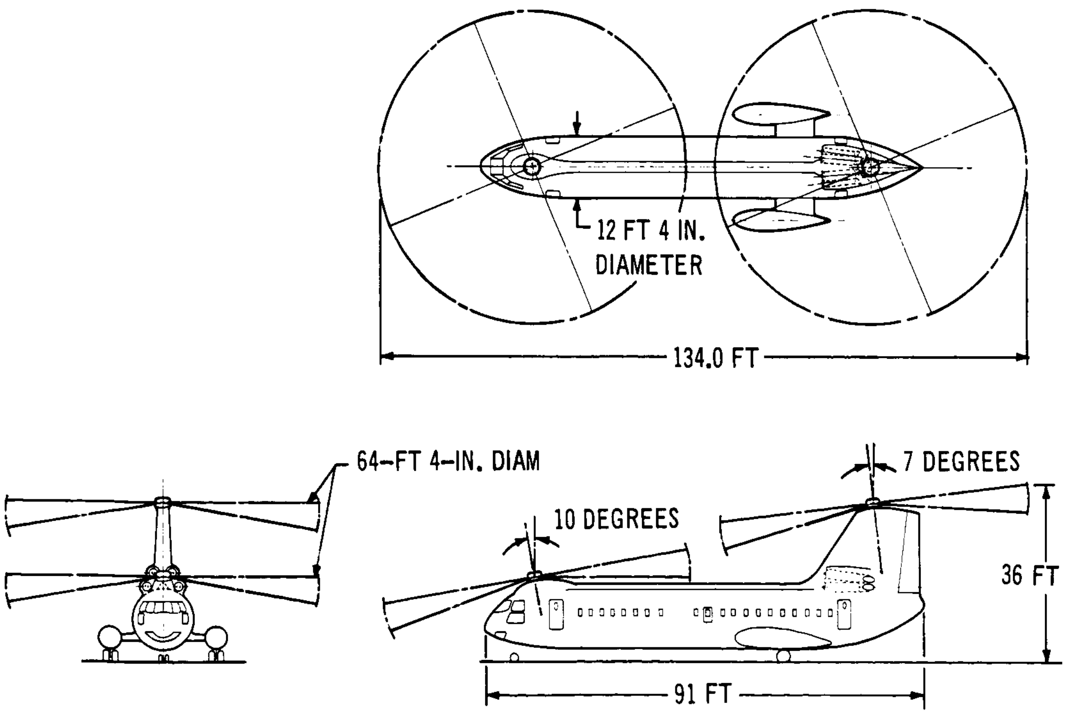


Figure 5: Helicopter VTOL—120-Passenger Capacity

TANDEM ROTORS ARE POWERED BY FOUR TURBOSHAFT ENGINES. THRUST OFFSET IS USED TO UNLOAD THE RETREATING BLADES AT HIGH SPEED AND THUS AVOID BLADE STALL. THE ROTORS INCORPORATE BOUNDARY LAYER CONTROL TO PERMIT OPERATION AT HIGH LIFT COEFFICIENTS WHEN THE ROTORS ARE SLOWED DOWN AND LIFT IS TRANSFERRED TO THE ADVANCING BLADES IN CRUISE.

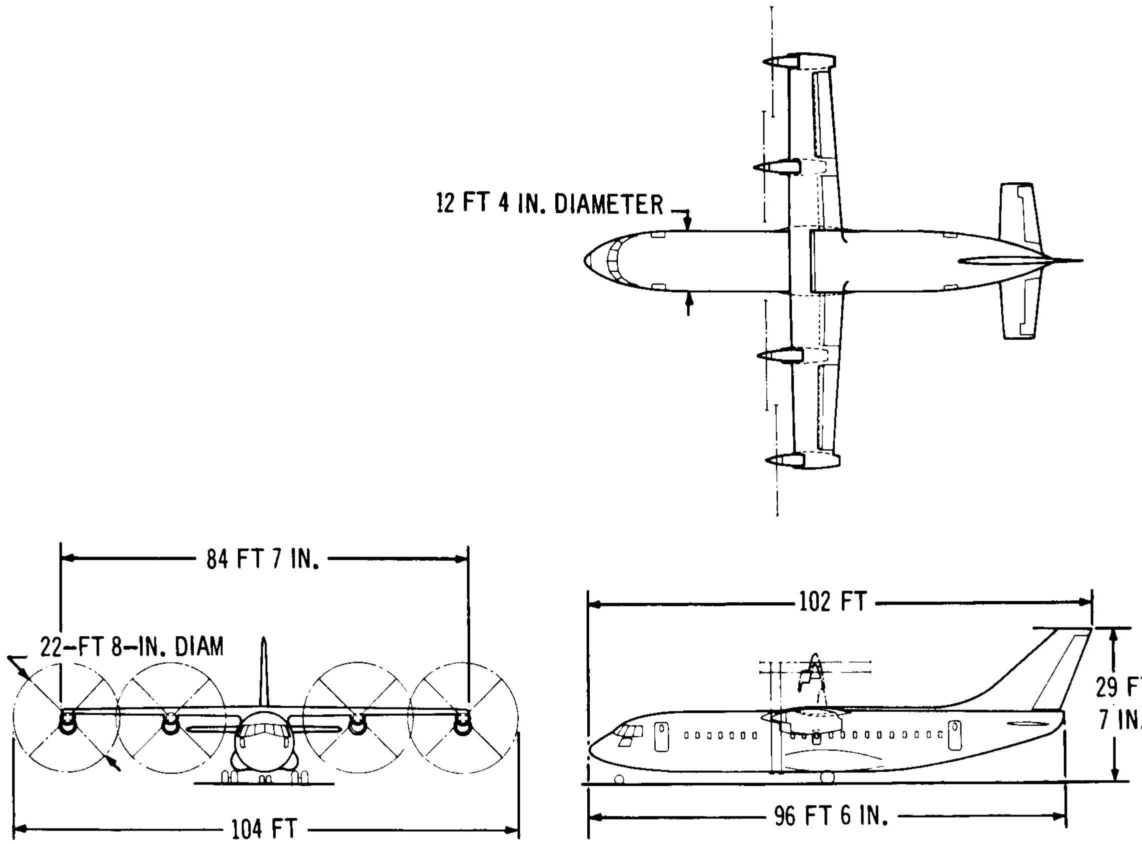


Figure 6: Tilt-Wing VTOL—120-Passenger Capacity

FOUR PROPELLERS DRIVEN BY FOUR INTERCONNECTED TURBOSHAFT ENGINES SUPPLY THE POWER FOR HOVER AND TILT FORWARD WITH THE WING TO SUPPLY CRUISE POWER. THE COMPLETE VERTICAL TAKEOFF SYSTEM IS CONTAINED WITHIN THE WING; THERE IS NO TAIL ROTOR, TAIL SHAFTING OR AFT GEAR BOX. IN HOVER, PITCH CONTROL IS PROVIDED BY MONOCYCLIC CONTROL AUGMENTED BY WING TILT LINKED TO LONGITUDINAL STICK MOTION, YAW CONTROL BY A SPOILER DEFLECTION SYSTEM AND ROLL CONTROL BY DIFFERENTIAL COLLECTIVE PROPELLER ANGLE.

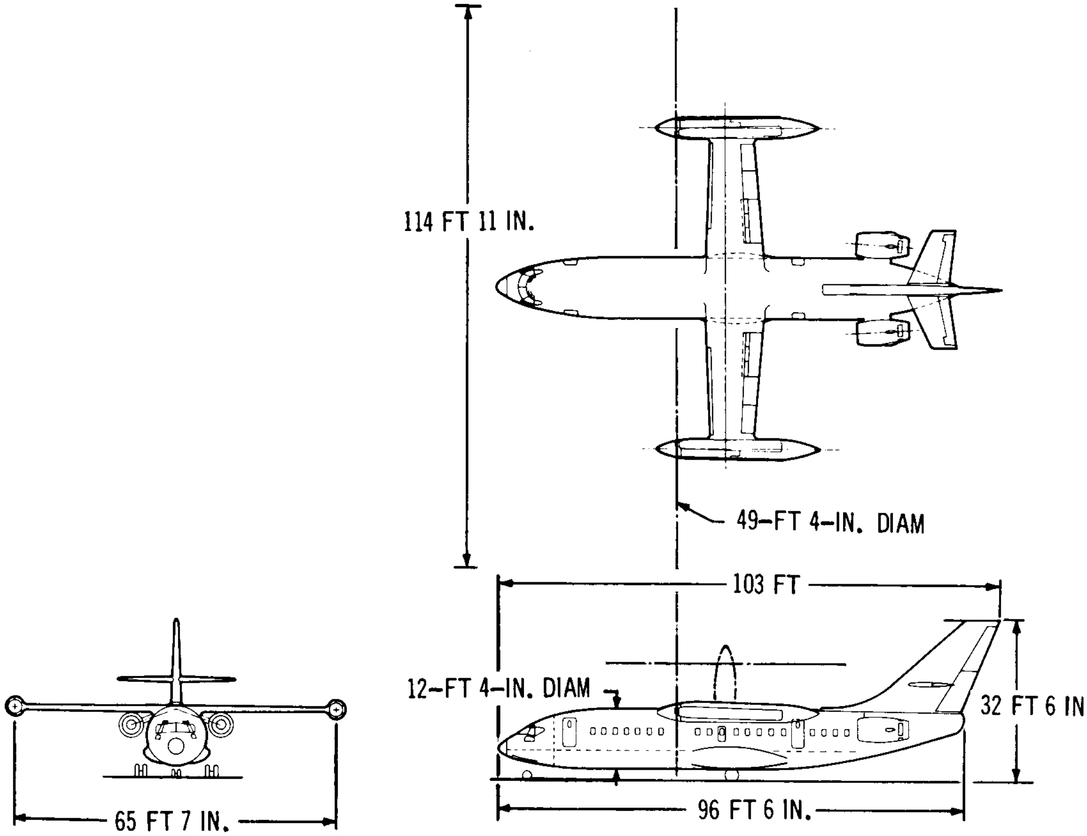
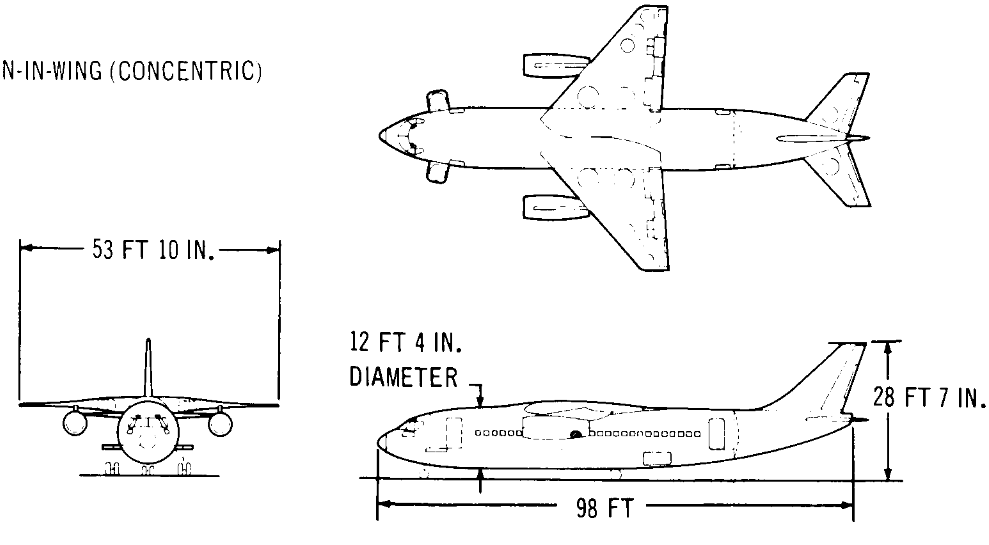


Figure 7: Folding Tilt Rotor VTOL—120-Passenger Capacity

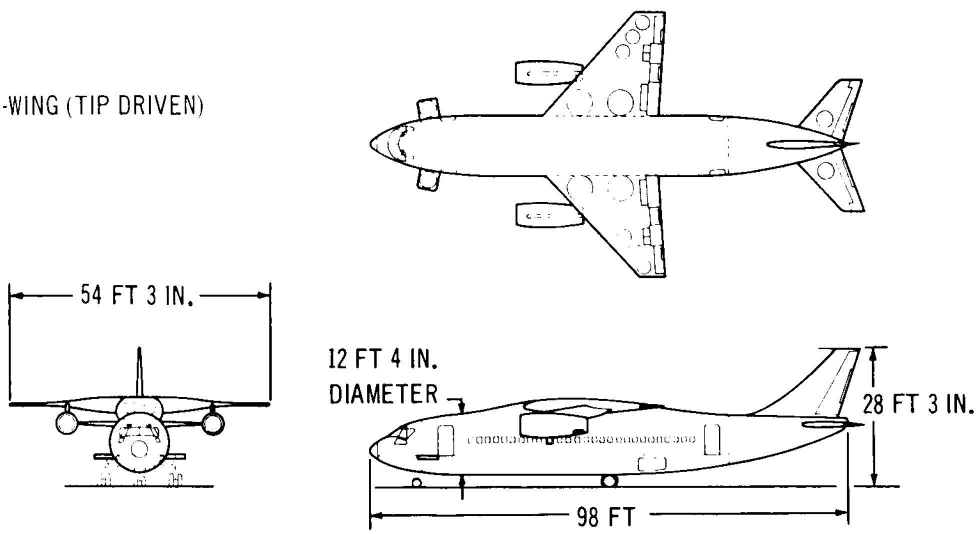
LIFT IS SUPPLIED BY THE ROTORS DURING HOVER AND TRANSITION. FOR CONVENTIONAL FLIGHT THE ROTORS ARE FEATHERED, STOPPED AND THE BLADES FOLDED REARWARD INTO WING TIP NACELLES. CONVERTIBLE FAN ENGINES PROVIDE SHAFT POWER FOR THE ROTOR DRIVE SYSTEM AND CONVERT TO GIVE FAN THRUST FOR THE CONVENTIONAL FLIGHT MODE.

VTOL-FAN-IN-WING (CONCENTRIC)



FOUR LIFT FANS OF BYPASS RATIO 10 ARE BURIED IN THE WING ROOTS AND TAKE THEIR POWER FROM CONCENTRICALLY MOUNTED GAS GENERATORS. THESE PLUS THE DEFLECTED THRUST FROM THE TWO CRUISE ENGINES SUPPLY THE POWER FOR HOVER. TWO GAS GENERATORS IN THE AFT FUSELAGE SUPPLY AIR TO POWER THE TIP DRIVEN CONTROL FANS IN THE WING TIPS, NOSE AND TAIL FOR CONTROL DURING HOVER.

VTOL-FAN-IN-WING (TIP DRIVEN)



FOUR GAS GENERATORS, HOUSED IN A FAIRING OVER THE FUSELAGE CENTER SECTION, ARE CROSS-DUCTED TO OPPOSING TIP DRIVEN LIFT FANS BURIED IN THE WING ROOTS. THESE GAS GENERATORS ARE OVERSIZED IN ORDER TO SUPPLY AIR TO POWER THE TIP DRIVEN CONTROL FANS IN THE WING TIPS, NOSE AND TAIL FOR CONTROL POWER DURING HOVER. THE THRUST FROM THE CRUISE ENGINES IS DEFLECTED DOWNWARD TO ADD TO THE THRUST FROM THE LIFT FANS IN HOVER.

Figure 8: Fan-in-Wing VTOL—120-Passenger Capacity

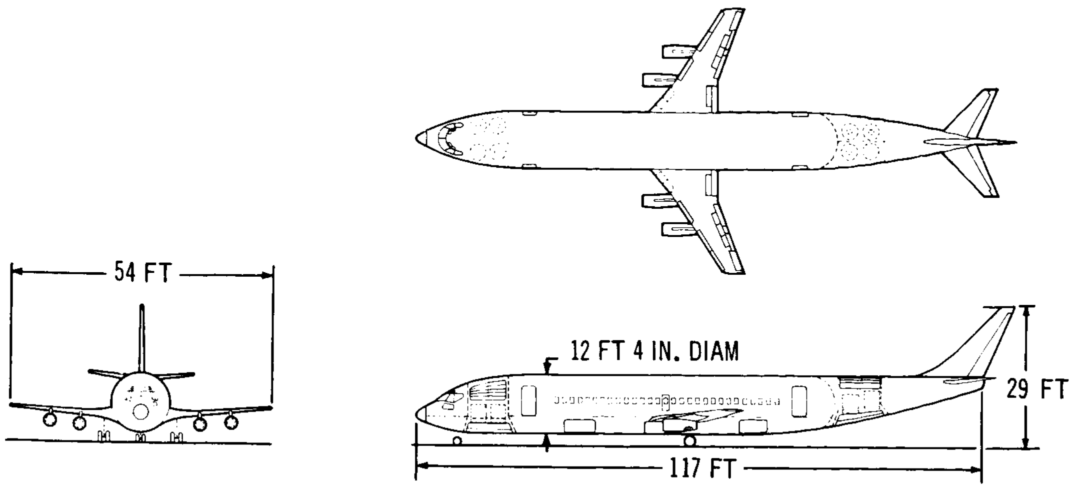


Figure 9: Jet Lift VTOL—120-Passenger Capacity

VERTICAL TAKEOFF IS ACCOMPLISHED WITH THE USE OF EIGHT AUXILIARY LIFT ENGINES IN THE BODY, PLUS THE DEFLECTED THRUST OF THE FOUR CRUISE ENGINES. CONTROL IN THE VERTICAL MODE IS BY DIFFERENTIAL ENGINE THRUST. THE HIGH WING LOADING ALLOWS SMOOTH, EFFICIENT HIGH SPEED CRUISE.

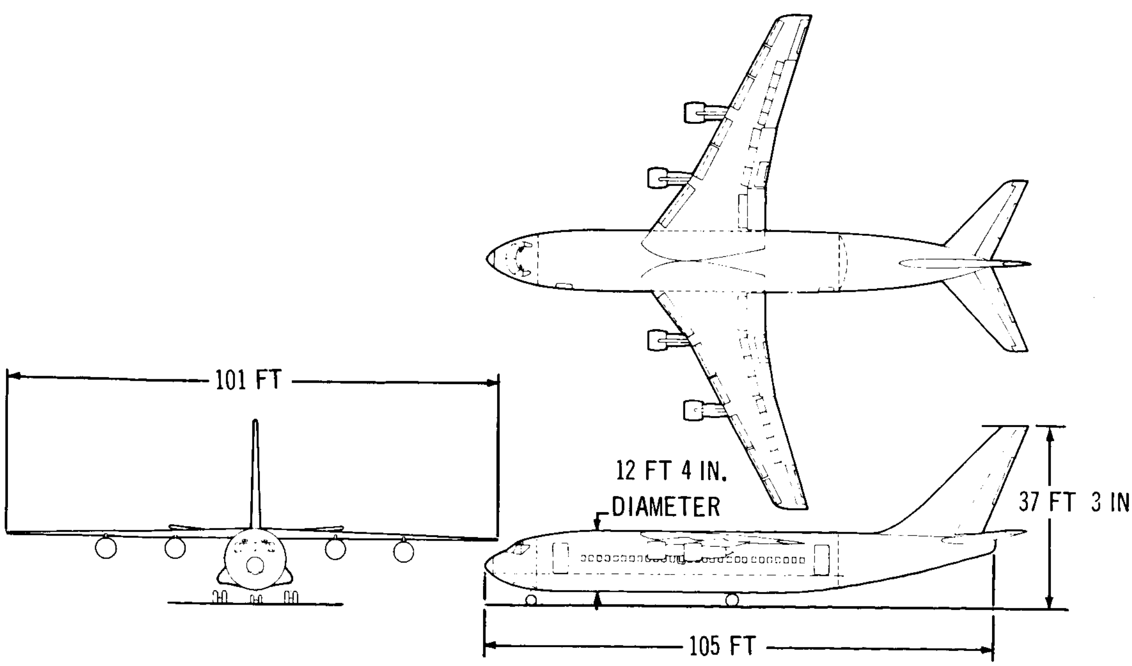


Figure 10: High Lift STOL—120-Passenger Capacity

EXTERNALLY BLOWN FLAPS ARE THE RELATIVELY SIMPLE HIGH LIFT DEVICES USED TO OBTAIN STOL PERFORMANCE. THE AFT SEGMENT OF THE INBOARD FLAPS ARTICULATE WITH THROTTLE MOVEMENT TO PROVIDE GLIDE PATH CONTROL. TWO DIFFERENT DESIGN WING LOADINGS ARE USED WITH THIS CONCEPT TO PROVIDE TWO DIFFERENT DESIGN FIELD LENGTHS.

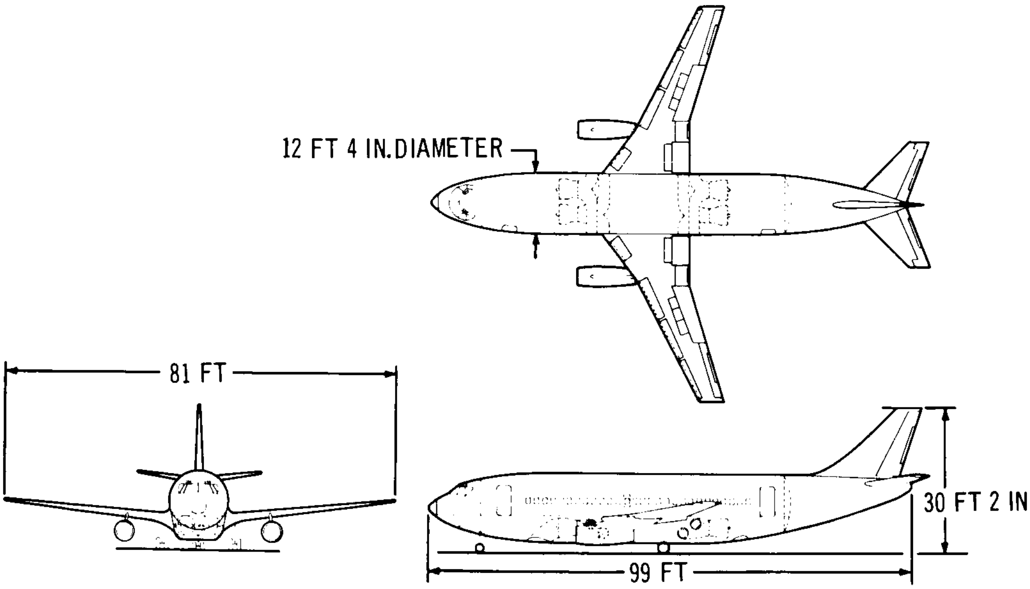


Figure 11: High Acceleration STOL--120-Passenger Capacity

FOUR AUXILIARY ENGINES ARE MOUNTED BENEATH THE FLOOR IN THE FUSELAGE TO PROVIDE ADDITIONAL THRUST FOR ACCELERATION IN TAKEOFF, LIFT ON APPROACH AND THRUST FOR DECELERATION AFTER LANDING. CONTROL IS SUPPLIED BY CONVENTIONAL AERODYNAMIC DEVICES IN THE STOL MODE.

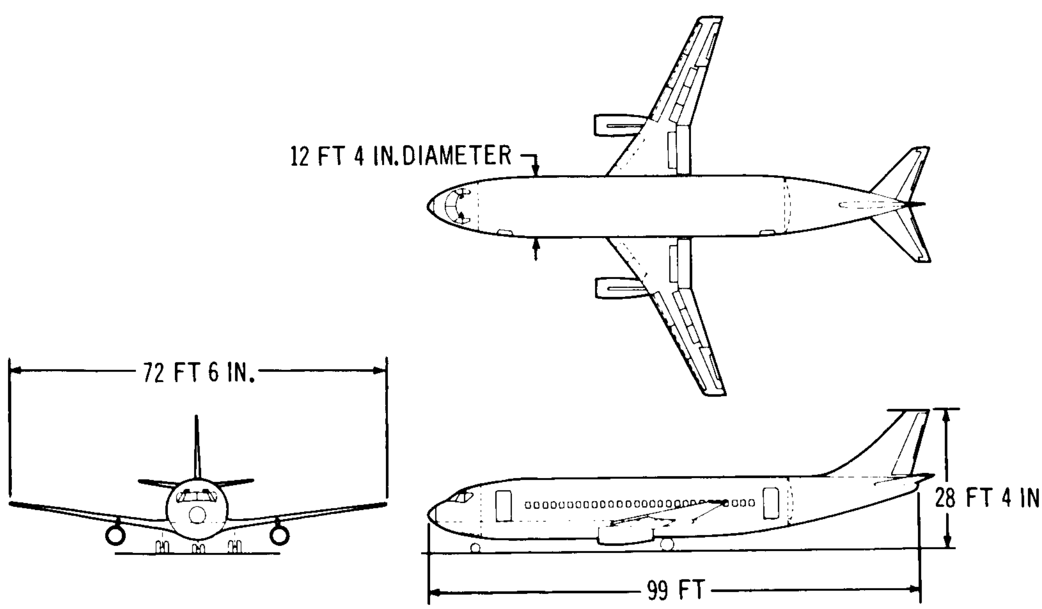


Figure 12: Conventional CTOL—120-Passenger Capacity

THIS AIRPLANE IS SIMILAR TO THE HIGH SPEED SHORT HAUL AIRCRAFT OF TODAY WITH THE 1985 TECHNOLOGY IN AERODYNAMICS, ENGINES AND STRUCTURES APPLIED.

Table 1: General Characteristics Summary

	Concentric Fan	Jet Lift	Hi-Accel STOL	Hi-Lift (w/s=60) STOL	Hi-Lift (w/s=90) STOL	CTOL (6 Min.-AMT)	Folding Tilt Rotor	Tilt Wing	Helicopter
Design Field Length* (ft)	VTOL	VTOL	1680	1650	2200	6000	VTOL	VTOL	VTOL
$C_{L_{MAX}}$	2.0	3.3	4.7	6.7	6.7	3.3	2.3	---	---
w/s	100/85/80	180/170/165	100	60	90	105	120	100	---
Disc Loading (psf)	---	---	---	---	---	---	22	50	13.3
Aspect Ratio	3.5/3.2/3.1	7	8.5	8.5	8.5	8.5	6.08	9.1	---
Λ C/4 (deg)	35	30	25	25	25	25	0	0	---
(t/c) Average	0.105	0.105	0.105	0.105	0.105	0.105	0.100	0.140	---
No. of Rotors	---	---	---	---	---	---	2	4	2
No. of Blades/Rotor	---	---	---	---	---	---	3	3	4
Solidity	---	---	---	---	---	---	0.09	0.226	0.093
Tip Speed (fps)	---	---	---	---	---	---	830	850	740
No. of Cruise Engines	2	4	2	4	4	2	2	4	4
Cruise T/W	0.45	0.34	0.31	0.37	0.37	0.33	0.398	---	---
No. of Lift Engines	4	8	4	---	---	---	---	---	---
Lift T/W	0.554	1.137	0.905	---	---	---	---	---	---
No. of Gas Generators for Reaction Control	2	---	---	---	---	---	---	---	---
Reaction Control T/W	0.3	---	---	---	---	---	---	---	---
Total T/W	1.304	1.477	1.215	0.37	0.37	0.33	0.398	---	---
Placard (KEAS)	420	430	430	300	400	430	430	400	250
N_{GUST} (max at V_{MO})	2.41	2.22	3.18	2.90	3.13	3.21	2.69	2.90	---
M_{cruise}	0.96	0.93	0.9	0.745	0.9	0.9	0.87	0.777	0.412
M_{CRIT}	0.953	0.911	0.903	0.903	0.902	0.901	0.886	0.775	---
$V_{APPROACH}$ (KEAS)	---	---	73	67	79	126	---	---	---
$V_{CONVERSION}$ (KEAS)	154	161	103	---	---	---	158	150	---
Payload/GW	0.337	0.357	0.335	0.365	0.370	0.390	0.285	0.3	0.317

*One engine out
89°F

	Design Capacity									
Cruise Thrust in lb (or HP) per Engine	90 120 200	13 500 16 900 26 700	4 760 6 020 9 550	9 230 11 700 18 600	5 170 6 570 10 420	5 000 6 290 10 000	8 500 10 600 17 000	13 100 16 610 27 210	5 910(HP) 7 450(HP) 12 310(HP)	3 750(HP) 4 320(HP) 5 950(HP)
Thrust per Lift Engine (lb)	90 120 200	8 310 10 400 16 400	8 000 10 000 15 930	13 450 17 100 27 050	---	---	---	---	---	---
Rotor Diameter (ft)	90 120 200	---	---	---	---	---	---	45 49 63	20 23 29	58 64 88
Overall Length (ft)	90 120 200	86 101 147	106 123 140	86 101 147	88 111 152	88 111 152	86 101 147	85 103 134	84 102 132	115 134 173
Wing Span (ft)	90 120 200	48 54 64	50 54 65	71 81 100	89 101 125	71 82 100	64 72 90	58 65 84	76 86 110	--- --- ---

Table 2: Weight Summary—All Concepts, 120-Passenger Capacity

120 PASSENGERS

	Conven-tional	STOL Hi-Accel	STOL Hi-Lift 1650 F. L.	STOL Hi-Lift 2200 F. L.	VTOL Jet Lift	VTOL Concentric Fan-In-Wing	VTOL Folding Tilt Rotor	VTOL Tilt Wing
Wing	3 650	5 000	7 670	5 250	2 550	3 180	3 560	4 400
Rotor							5 190	
Tail	1 200	1 430	2 220	1 720	810	1 330	1 820	1 700
Body	7 370	8 220	7 740	7 690	8 730	7 520	7 580	8 190
Landing Gear	2 000	2 460	2 590	2 500	2 290	2 480	2 770	2 590
Nacelles	890	5 630	1 140	1 100	2 760	2 990	1 870	1 360
(Structure)	(15 110)	(22 740)	(21 360)	(18 260)	(17 140)	(17 500)	(22 790)	(18 240)
Lift Fans						3 140		
Cruise Engines	2 060	2 280	2 450	2 370	2 250	3 140	3 270	3 010
Lift Engines		3 030			3 530			
Engine Controls	60	140	120	120	360	180	200	200
Fuel System	750	590	550	570	570	600	590	590
Starting System	120	180	240	240	360	180	120	240
Lubrication System							50	80
Propellers							*110	3 890
Drive System							6 590	4 540
(Powerplant)	(2 990)	(6 220)	(3 360)	(3 300)	(7 070)	(7 240)	(10 930)	(12 550)
Instruments	540	570	550	550	620	570	540	540
Flight Controls	1 010	1 070	2 080	1 700	940	1 200	3 470	4 220
Hydraulics	250	350	370	310	320	310	380	400
Electrical	1 570	1 570	1 570	1 570	1 570	1 570	1 570	1 570
Electronics	540	540	540	540	540	540	540	540
Furnishings	6 780	7 230	6 850	6 850	7 380	6 960	7 150	7 150
Air Cond., Anti-Ice	1 770	1 820	1 800	1 800	1 900	1 820	1 940	1 940
APU	770	770	770	770	770	770	770	770
Aux Gear Grp	40	40	40	40	40	40	40	40
Reaction Control						3 280	280	
(Fixed Equipment)	(13 270)	(13 960)	(14 570)	(14 130)	(14 080)	(17 060)	(16 680)	(17 170)
Weight Empty	31 370	42 920	39 290	35 690	38 290	41 800	50 400	47 960
Crew and Baggage	660	660	660	660	660	660	660	660
Unusable Fuel & Oil	390	490	470	470	690	490	390	470
Passenger Service	790	790	790	790	790	790	790	790
(Useful Load)	(1 840)	(1 940)	(1 920)	(1 920)	(2 140)	(1 940)	(1 840)	(1 920)
Operating Wt. Empty	33 210	44 860	41 210	37 610	40 430	43 740	52 240	49 880
Passengers	19 800	19 800	19 800	19 800	19 800	19 800	19 800	19 800
Luggage & Cargo	4 200	4 200	4 200	4 200	4 200	4 200	4 200	4 200
Fuel	7 410	6 800	5 900	6 430	6 470	7 650	7 320	6 720
Gross Weight	64 620	75 660	71 110	68 040	70 900	75 392	83 560	80 600

*Exhaust & Cooling

Conversion factor for international units (lb x .454 = kg)

Table 3: Weight Summary—All Concepts, 200-Passenger Capacity

200 PASSENGERS

	Conven-tional	STOL Hi-Accel	STOL Hi-Lift 1650 F. L.	STOL Hi-Lift 2200 F. L.	VTOL Jet Lift	VTOL Concentric Fan-In-Wing	VTOL Folding Tilt Rotor	VTOL Tilt Wing	VTOL Heli-copter
Wing	6 340	8 500	12 550	8 720	4 340	5 420	6 850	7 690	
Rotor							9 660		7 690
Tail	2 070	2 350	3 630	2 790	1 360	1 920	2 700	2 680	*420
Body	11 220	12 600	11 500	11 430	13 520	11 460	11 900	13 040	8 500
Landing Gear	3 130	3 830	4 050	3 900	3 660	3 980	4 700	4 270	2 560
Nacelles	1 330	9 090	2 050	1 980	5 040	4 420	3 360	2 160	500
(Structure)	(24 090)	(36 370)	(33 780)	(28 820)	(27 920)	(27 200)	(39 170)	(29 840)	(19 670)
Lift Fans						3 940			
Cruise Engines	3 130	3 430	3 840	3 690	3 590	5 060	6 040	4 700	2 900
Lift Engines		4 720			5 640				**200
Engine Controls	60	140	120	120	360	180	200	250	180
Fuel System	850	690	660	690	690	740	750	750	800
Starting System	120	180	240	240	360	180	120	240	240
Lubrication System							80	120	100
Propellers								7 250	1 800
Drive System							12 140	8 400	11 740
(Powerplant)	(4 160)	(9 160)	(4 860)	(4 740)	(10 640)	(10 100)	(19 330)	(21 710)	(17 960)
Instruments	540	570	550	550	620	570	540	540	540
Flight Controls	1 230	1 300	2 960	2 370	1 040	1 350	6 510	7 910	8 850
Hydraulics	390	540	590	490	510	490	630	660	400
Electrical	1 750	1 750	1 750	1 750	1 750	1 750	1 750	1 750	1 750
Electronics	550	550	550	550	550	550	550	550	550
Furnishings	11 210	11 670	11 280	11 280	11 810	11 390	11 580	11 580	11 580
Air Cond., Anti-Ice	2 100	2 180	2 140	2 140	2 280	2 180	2 340	2 340	2 340
APU	1 100	1 100	1 100	1 100	1 100	1 100	1 100	1 100	1 100
Aux Gear Grp	40	40	40	40	40	40	40	40	40
Reaction Control						6 430	500		
(Fixed Equipment)	(18 910)	(19 700)	(20 960)	(20 270)	(19 700)	(25 850)	(25 540)	(26 470)	(27 150)
Weight Empty	47 160	65 230	59 600	53 830	58 260	63 150	84 040	78 020	64 780
Crew and Baggage	800	800	800	800	800	800	800	800	800
Unusable Fuel & Oil	550	710	650	650	890	670	550	650	650
Passenger Service	1 290	1 290	1 290	1 290	1 290	1 290	1 290	1 290	1 290
(Useful Load)	(2 640)	(2 800)	(2 740)	(2 740)	(2 980)	(2 760)	(2 640)	(2 740)	(2 740)
Operating Wt. Empty	49 800	68 030	62 340	56 570	61 240	65 910	86 680	80 760	67 520
Passengers	33 000	33 000	33 000	33 000	33 000	33 000	33 000	33 000	33 000
Luggage & Cargo	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000
Fuel	11 110	10 040	8 740	9 490	10 130	11 140	11 910	10 810	13 460
Gross Weight	100 910	118 070	111 080	106 060	111 370	117 050	138 590	131 570	120 980

*Pylon

**Air induction and exhaust

Conversion factor for international units (lb x .454 = kg)

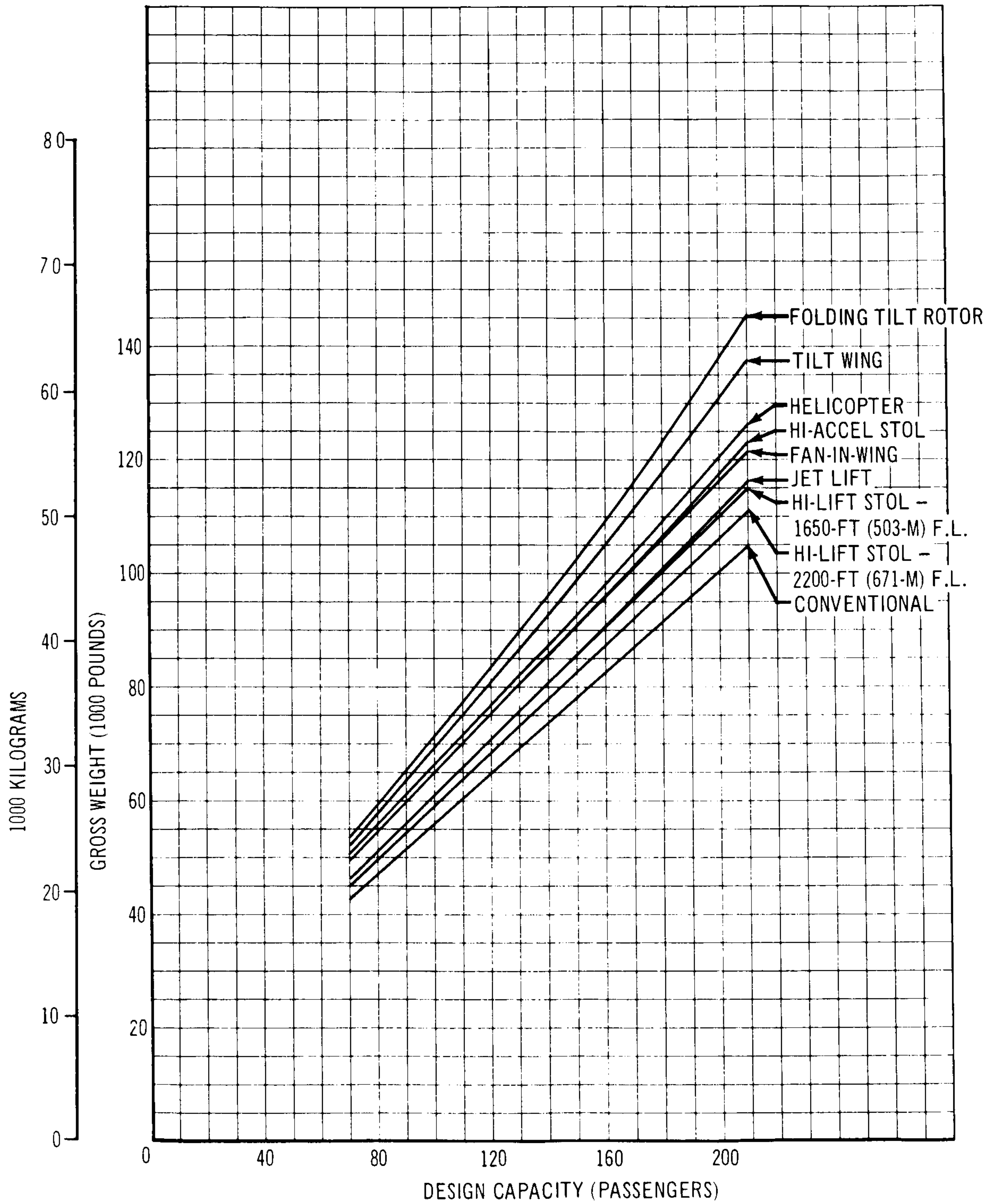


Figure 13: Gross Weight Comparison

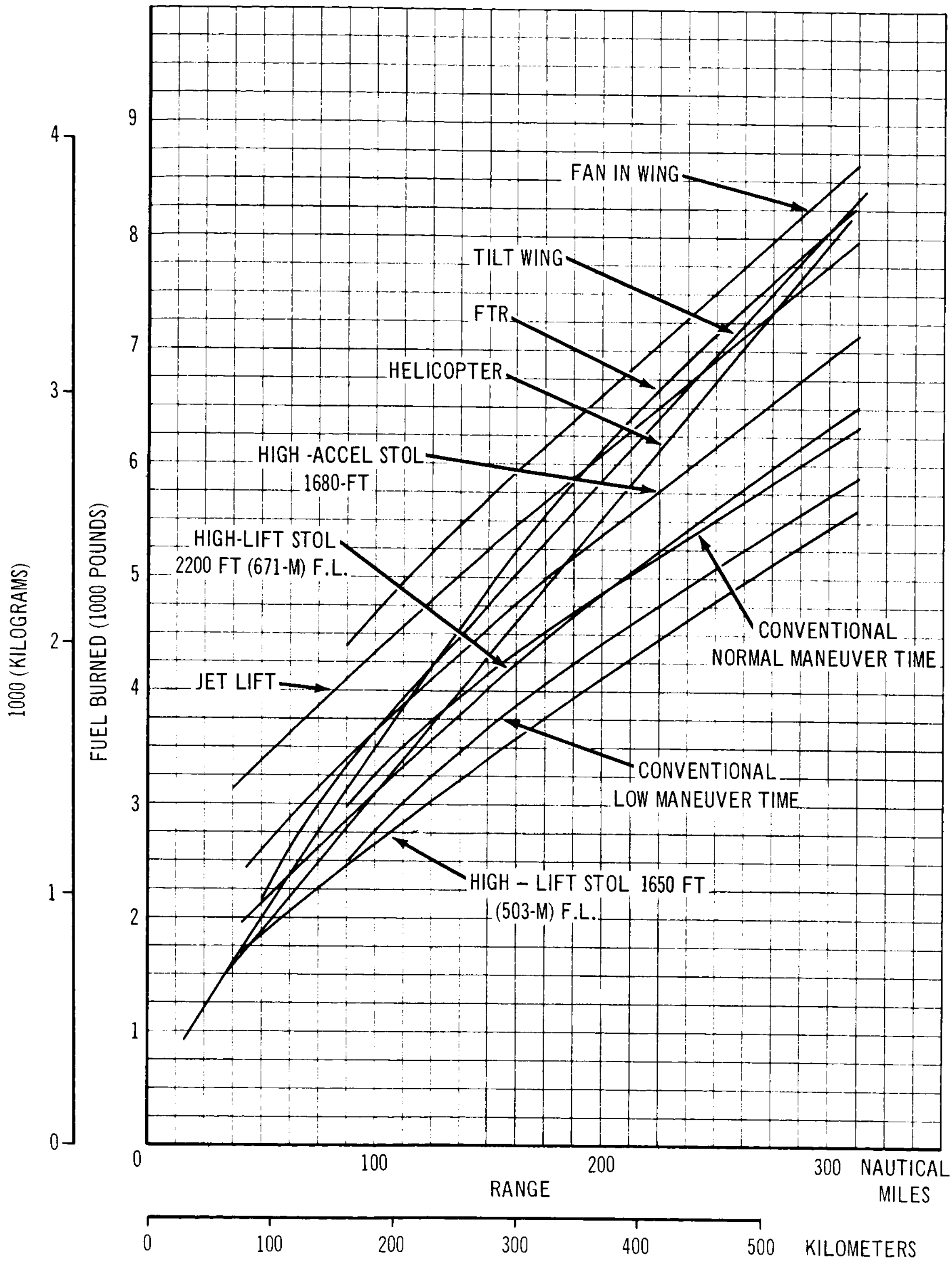


Figure 14: Comparison of Fuel Burned

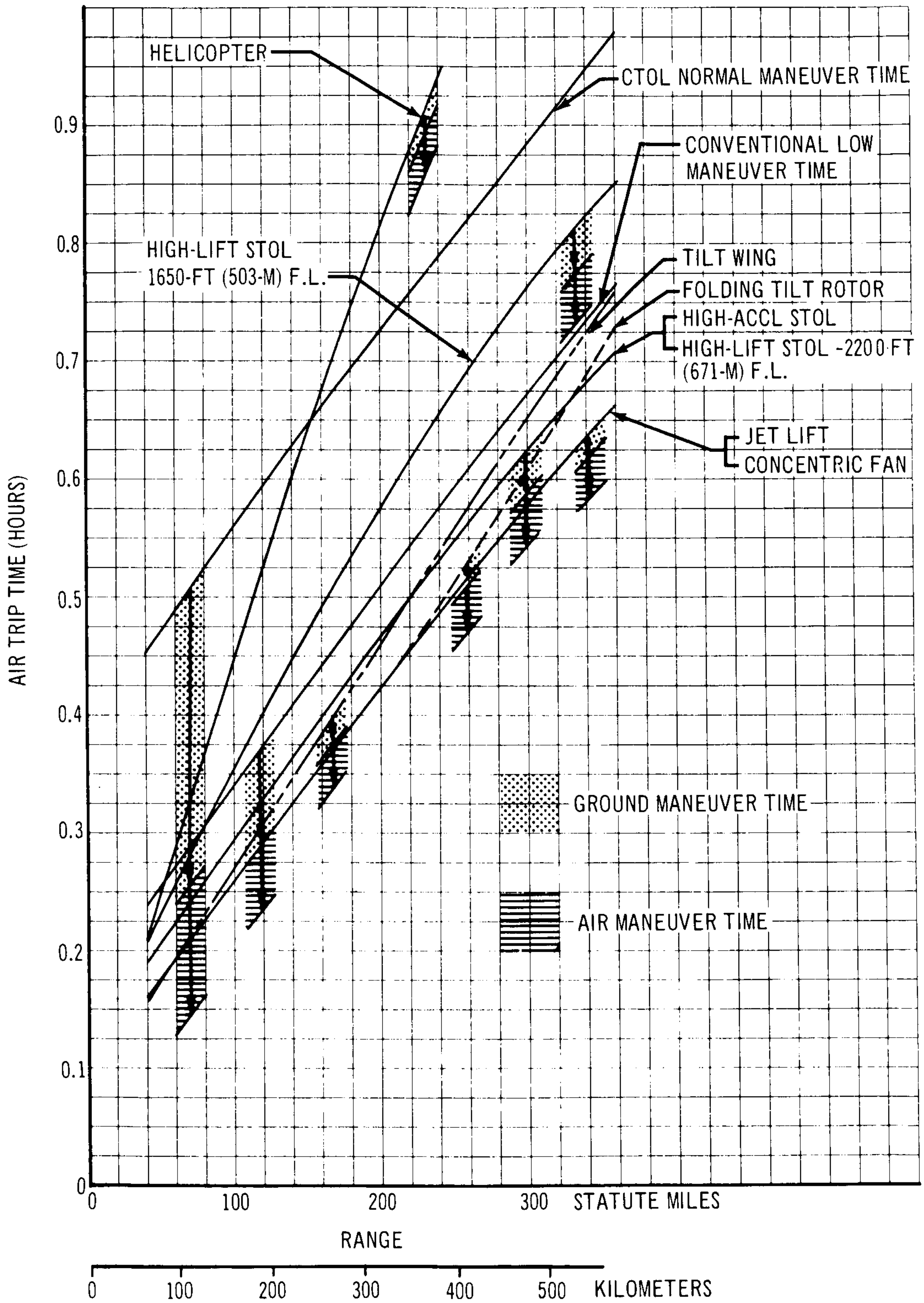


Figure 15: Air Trip Time Comparison

Throughout the report the design field length descriptions accompanying the titles of the various STOL designs are generally written as a basic single number in feet. However, it should be recognized that, depending on the rules used to define design field length, the actual field performance can differ from this number by several hundred feet. The basic number defines the maximum distance required.

Table 1 summarizes the general characteristics of all concepts in addition to the propulsion system details. Tables 2 and 3 present the weight summary for each concept for two typical design capacities.

6.4 Operating Costs

Both direct and indirect operating cost estimates are made as a result of component by component analysis of both the aircraft and the transportation system. Table 4 shows the total aircraft acquisition price and also breaks down the total price to airframe, cruise engines, and lift engines.

Direct Operating Costs.—The direct operating cost estimates for the basic mission assumptions are shown in figs. 16, 17 and 18 for each size configuration analyzed. The usual decreasing trend of DOC level with increasing airplane design capacity is evident, but of more importance is the resulting smaller differences in DOC value between concepts as design capacity is increased. This suggests, for sake of comparison, the consideration of the operating cost difference between groups of concepts and associated environment, as more readily discernible, than between specific concepts.

Indirect Operating Costs.—Typical indirect operating cost estimates for the postulated transportation system are shown in figs. 19, 20 and 21.

The basic estimates as shown in fig. 19 include the allocation of the full depreciation costs of the VTOL and STOL terminal facilities (not including the land); whereas the CTOL allocation is determined as a mean between the current levels of U.S. Domestic trunk operators and the local service airlines.

The variation in IOC level between each of the VTOL concepts and between each of the STOL concepts is negligible, hence the narrow band to cover several concepts.

If the V/STOL terminal facilities depreciation charge is reduced to the same magnitude as the CTOL, the IOC levels are as shown in figs. 22, 23 and 24.

Table 4: Airplane Acquisition Price

90-PASSENGER CAPACITY

	Helicopter	Tiltwing	Folding tilt rotor	Fan in wing (concentric)	Fan in wing (tip drive)	Jet lift	Hi-lift STOL 1 650 ft (5 03 m)	Hi Accel STOL 1 680 ft (5 12 m)	Hi-Lift STOL 2 200 ft (6 71 m)	CTOL low maneuver time	CTOL normal maneuver time
Airframe	$1 986 410	$2 283 515	$2 319 469	$2 185 079		$1 952 617	$2 373 118	$2 363 459	$2 363 459	$1 804 116	$1 810 357
Lift Fan				206 197							
Dynamic System	384 945	279 431	383 898								
Lift Engines				384 722		893 501		524 804			
Secondary Gas Generators				174 325							
Cruise Engines	288 000	391 488	507 584	490 223		432 196	447 954	359 148	438 035	319 216	322 119
TOTAL	$2 659 355	$2 954 434	$3 210 951	$3 440 546		$3 278 314	$2 821 072	$3 247 411	$2 608 038	$2 123 332	$2 132 476

120-PASSENGER CAPACITY

	Helicopter	Tiltwing	Folding tilt rotor	Fan in wing (concentric)	Fan in wing (tip drive)	Jet lift	Hi-lift STOL 1 650 ft (5 03 m)	Hi Accel STOL 1 680 ft (5 12 m)	Hi-Lift STOL 2 200 ft (6 71 m)	CTOL low maneuver time	CTOL normal maneuver time
Airframe		$2 710 032	$2 648 347	$2 611 169		$2 394 912	$2 740 949	$2 825 546	$2 560 295	$2 298 273	$2 302 502
Lift Fan				238 472							
Dynamic System		352 713	463 261								
Lift Engines				406 400		961 587		568 428			
Secondary Gas Generators				209 121							
Cruise Engines		465 600	568 777	595 387		499 144	514 302	442 820	501 520	385 252	387 076
TOTAL		$3 528 345	$3 680 385	$4 060 549		$3 855 643	$3 255 251	$3 836 794	$3 061 815	$2 683 525	$2 689 578

200-PASSENGER CAPACITY

	Helicopter	Tiltwing	Folding tilt rotor	Fan in wing (concentric)	Fan in wing (tip drive)	Jet lift	Hi-lift STOL 1 650 ft (5 03 m)	Hi Accel STOL 1 680 ft (5 12 m)	Hi-Lift STOL 2 200 ft (6 71 m)	CTOL low maneuver time	CTOL normal maneuver time
Airframe	$3 237 876	$4 118 016	$3 944 916	$3 797 118	$3 968 968	$3 525 261	$3 931 308	$4 030 359	$3 654 323	$3 286 935	$3 293 276
Lift Fan				312 020	378 432						
Dynamic System	736 800	582 689	857 020								
Lift Engines				450 885	487 494	1 098 955		816 175			
Secondary Gas Generators				258 065	278 000						
Cruise Engines	393 600	697 392	879 912	872 060	983 054	707 797	729 408	645 582	706 072	565 175	562 265
TOTAL	$4 368 276	$5 398 097	$5 681 848	$5 690 148	$6 095 918	$5 332 013	$4 660 716	$5 492 116	$4 360 395	$3 852 110	$3 861 541

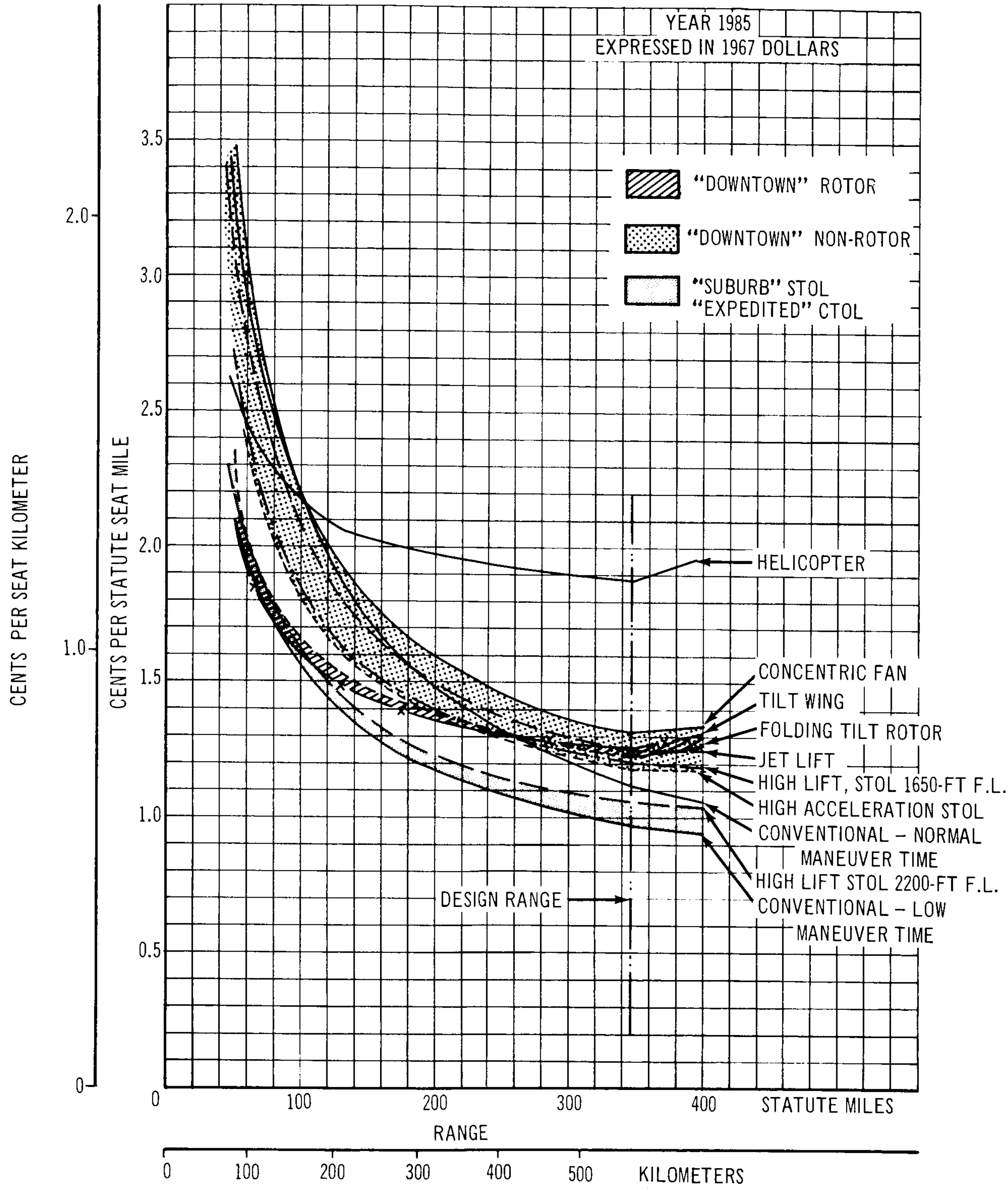


Figure 16: Direct Operating Cost—90-Passenger Capacity

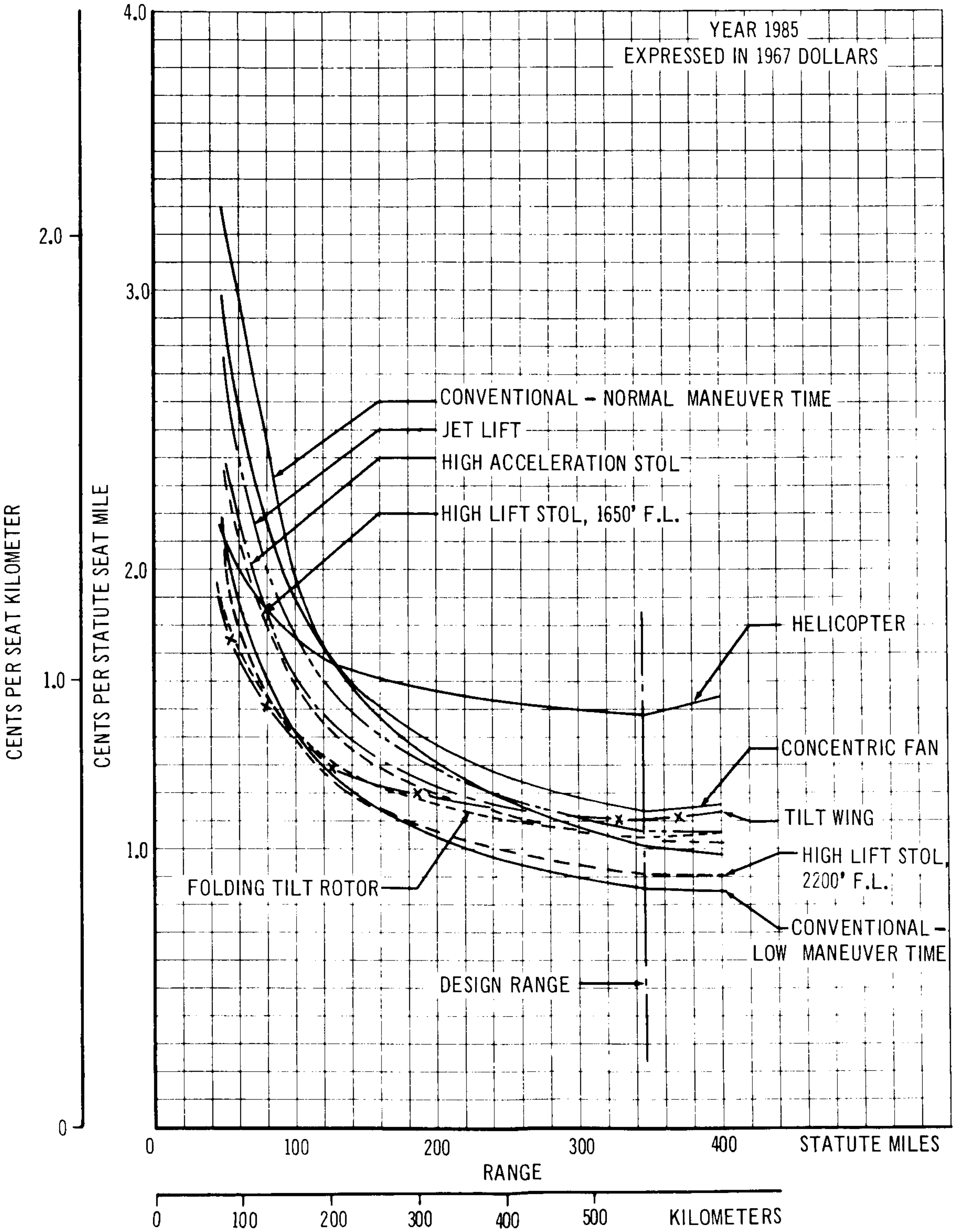


Figure 17: Direct Operating Cost—120-Passenger Capacity

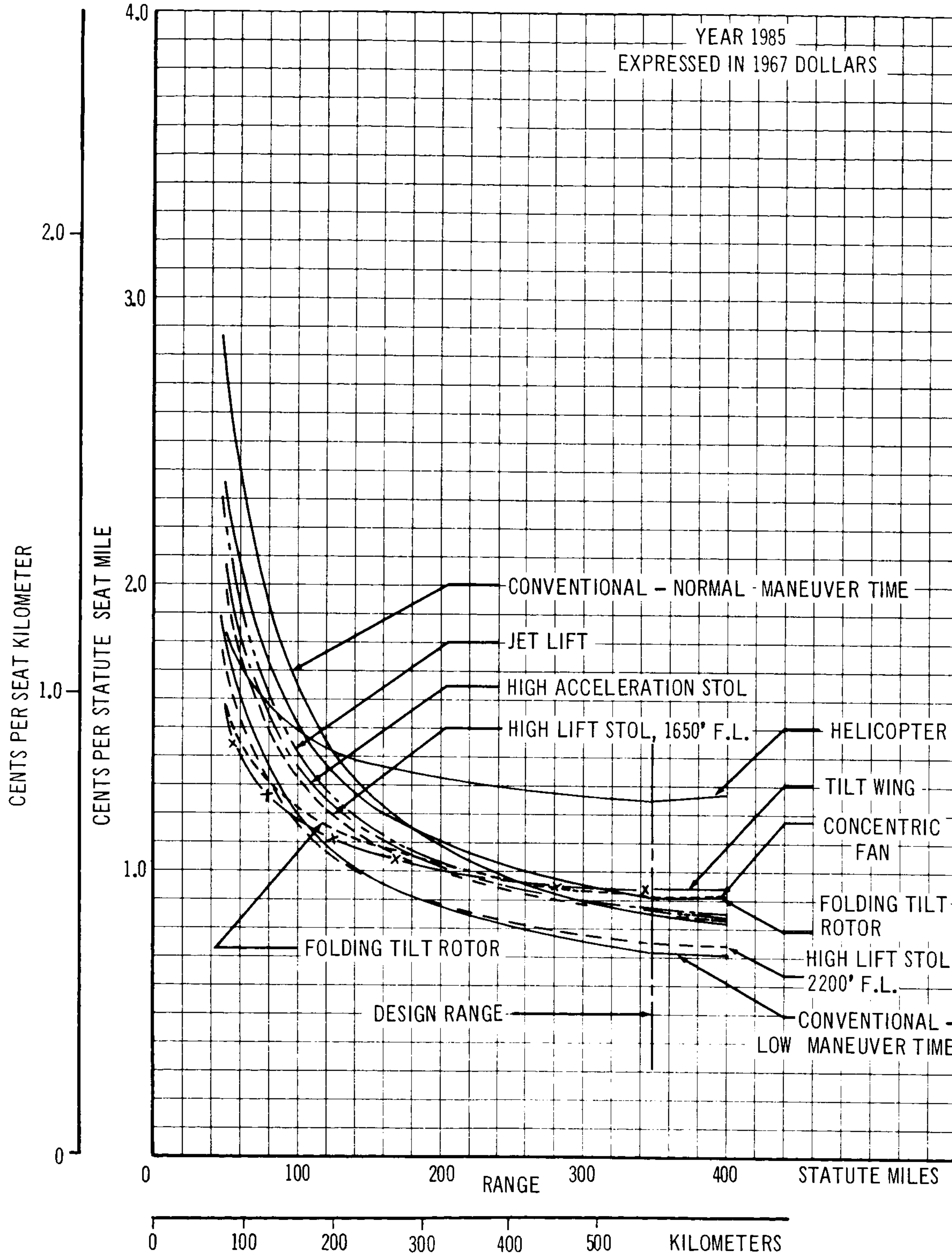


Figure 18: Direct Operating Cost—200-Passenger Capacity

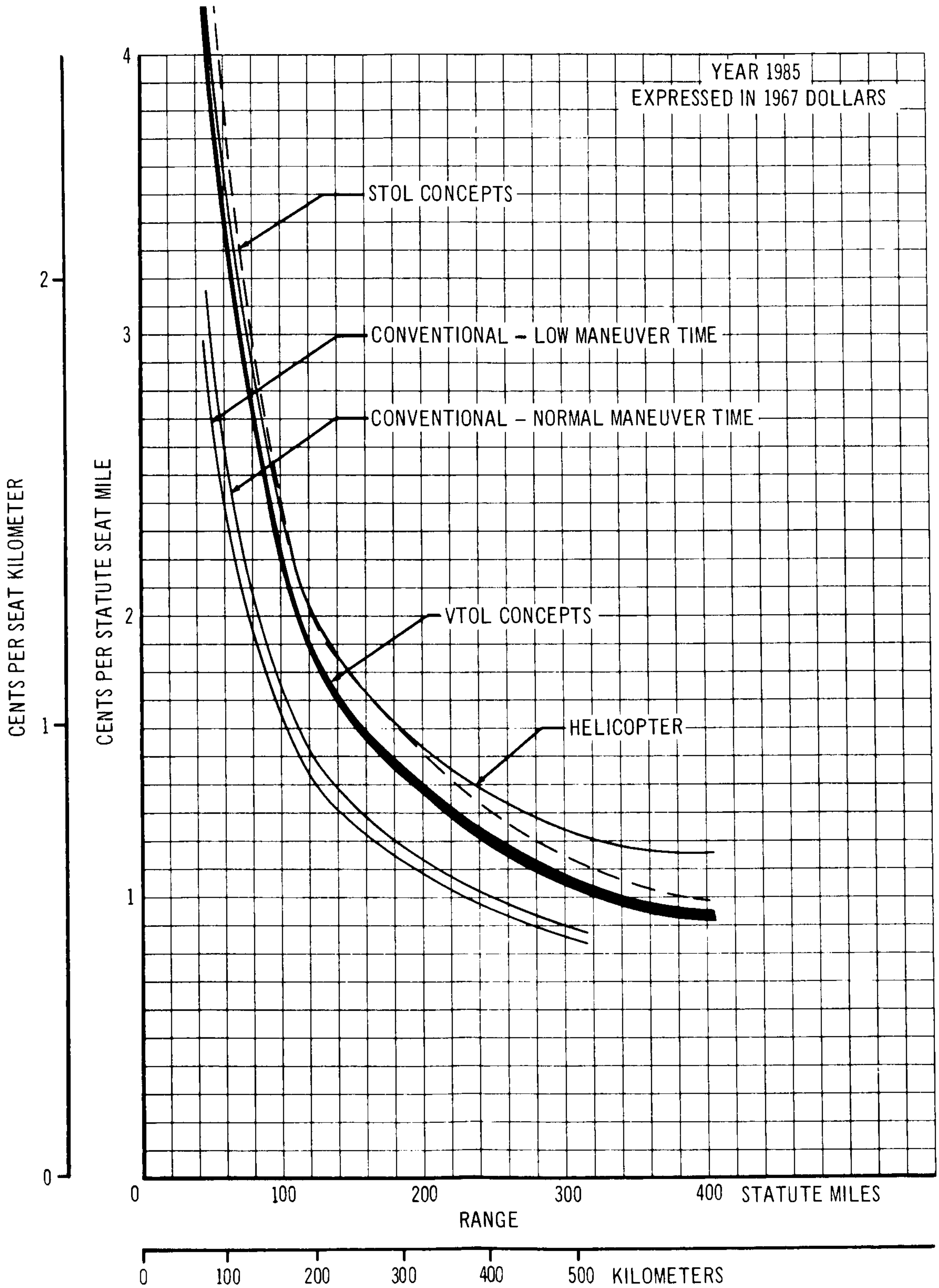


Figure 19: Indirect Operating Cost—90-Passenger Capacity

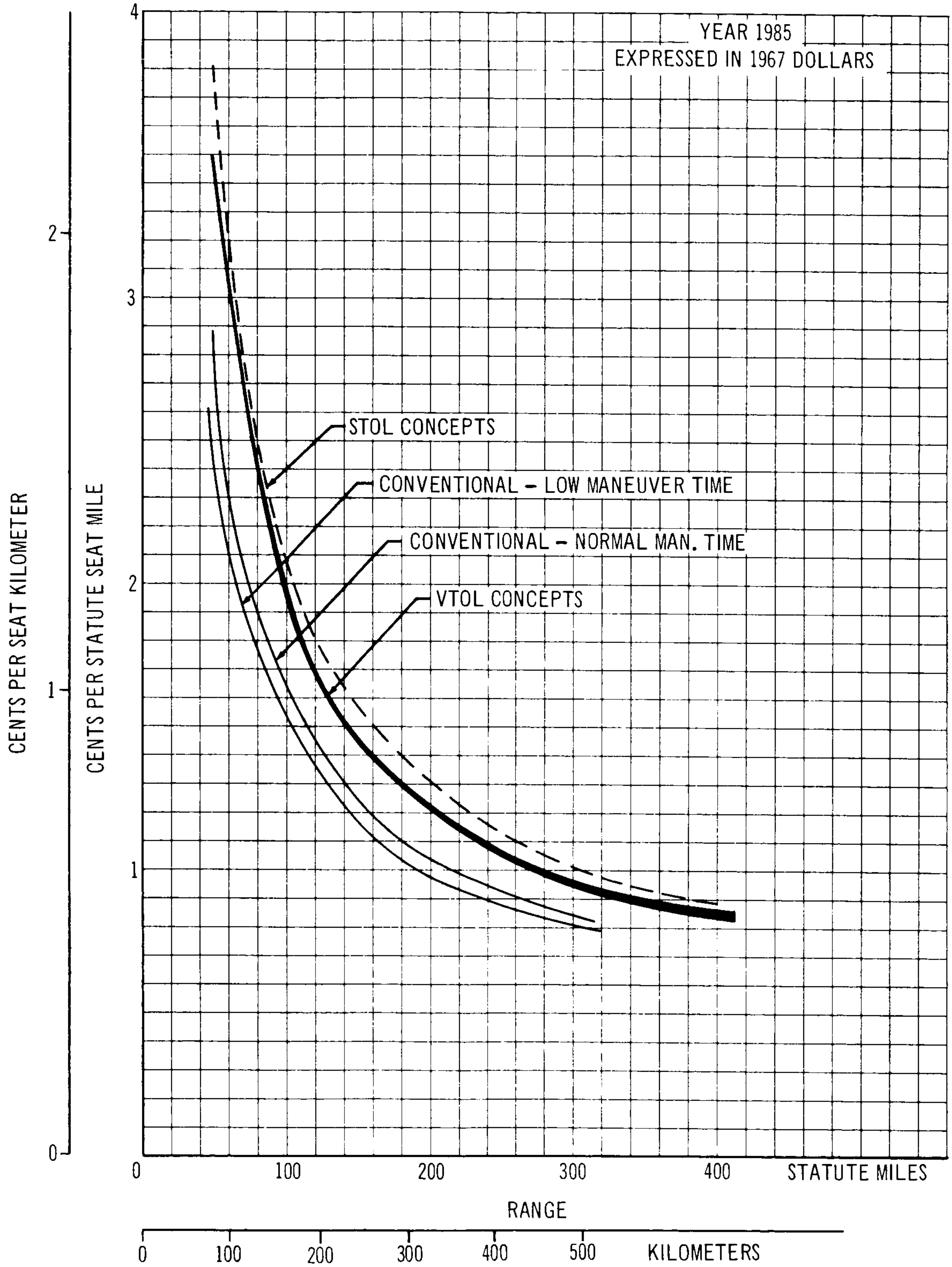


Figure 20: Indirect Operating Cost—120-Passenger Capacity

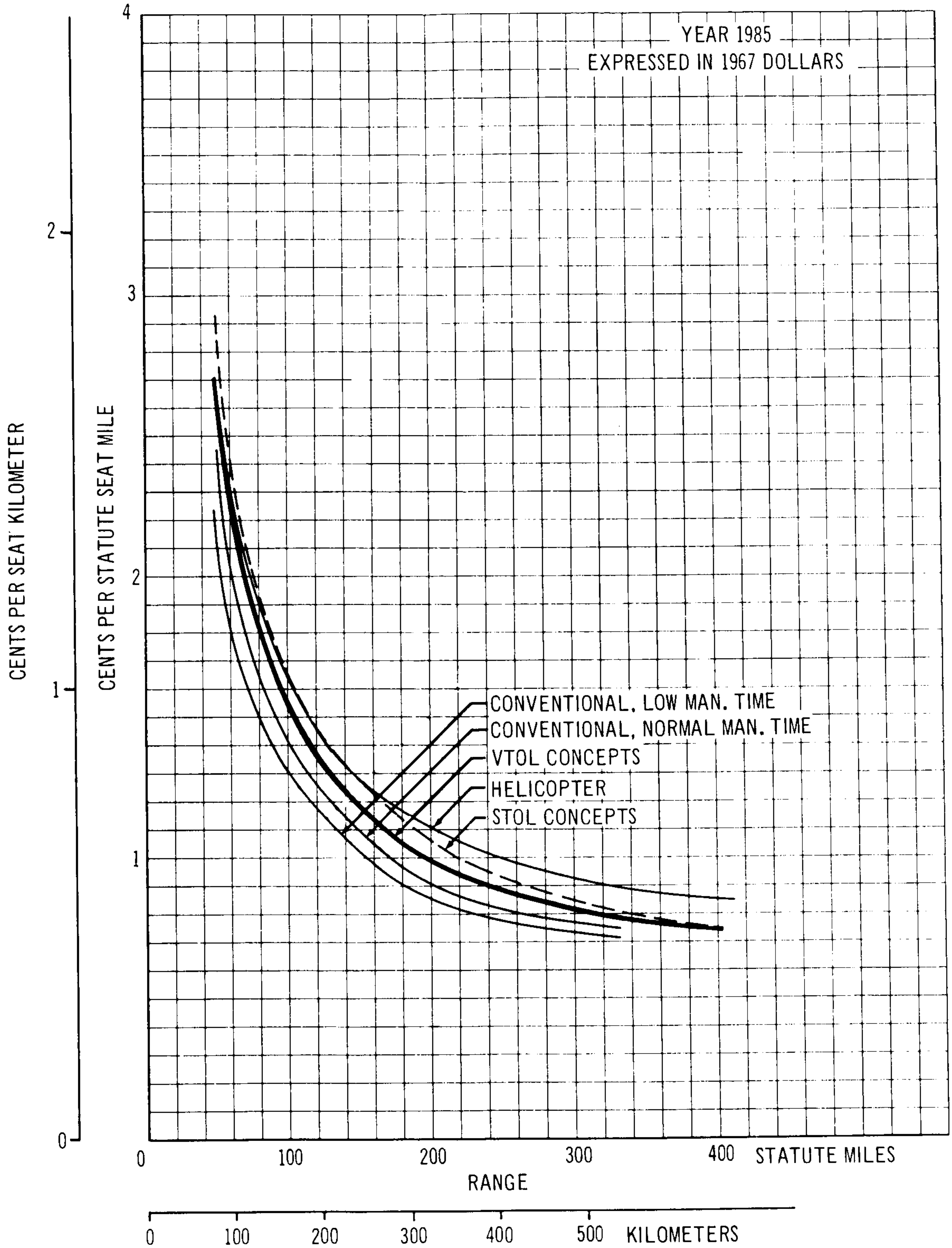


Figure 21: Indirect Operating Cost—200-Passenger Capacity

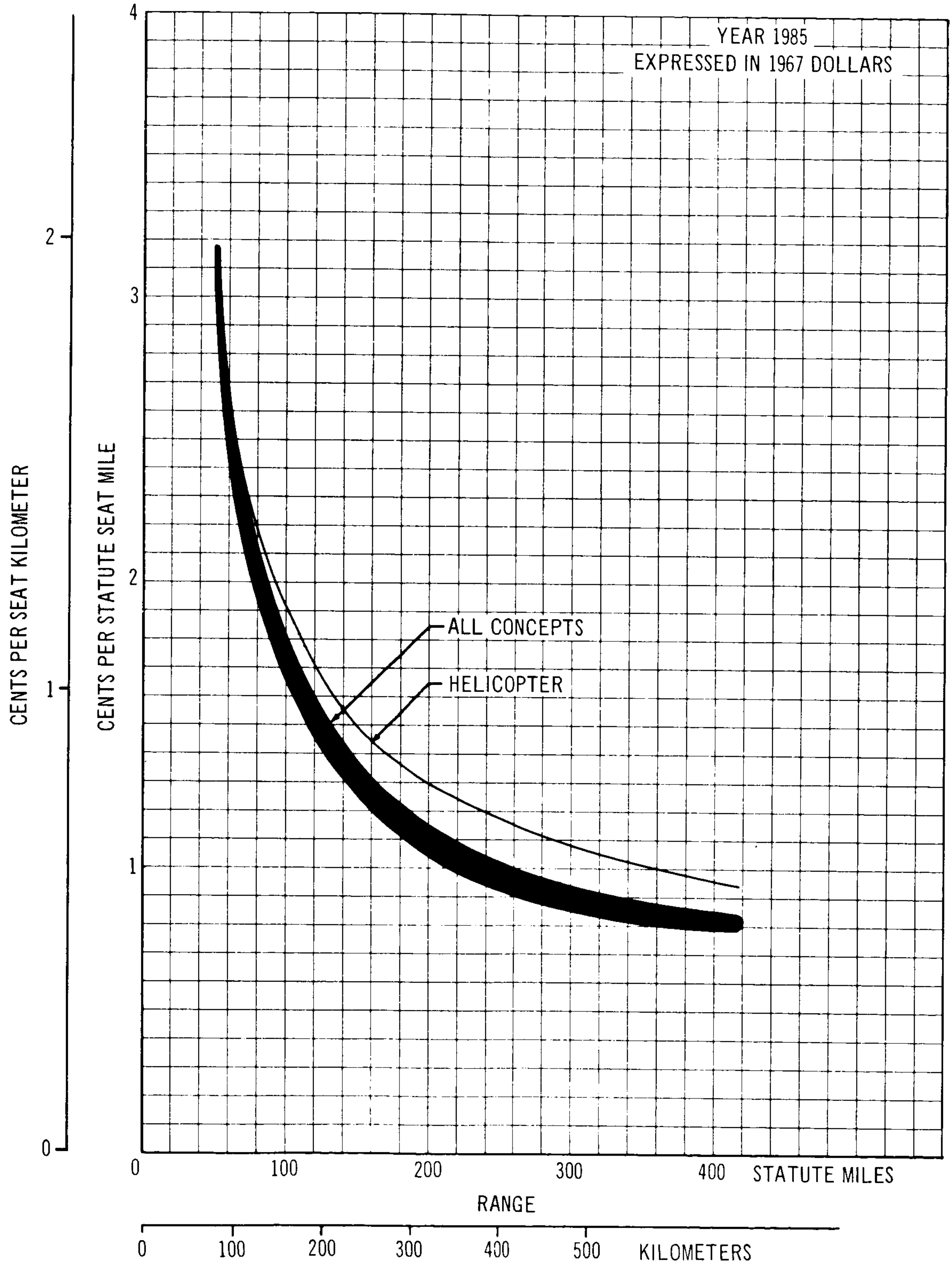


Figure 22: Indirect Operating Cost—90-Passenger Capacity, Reduced Facilities Depreciation

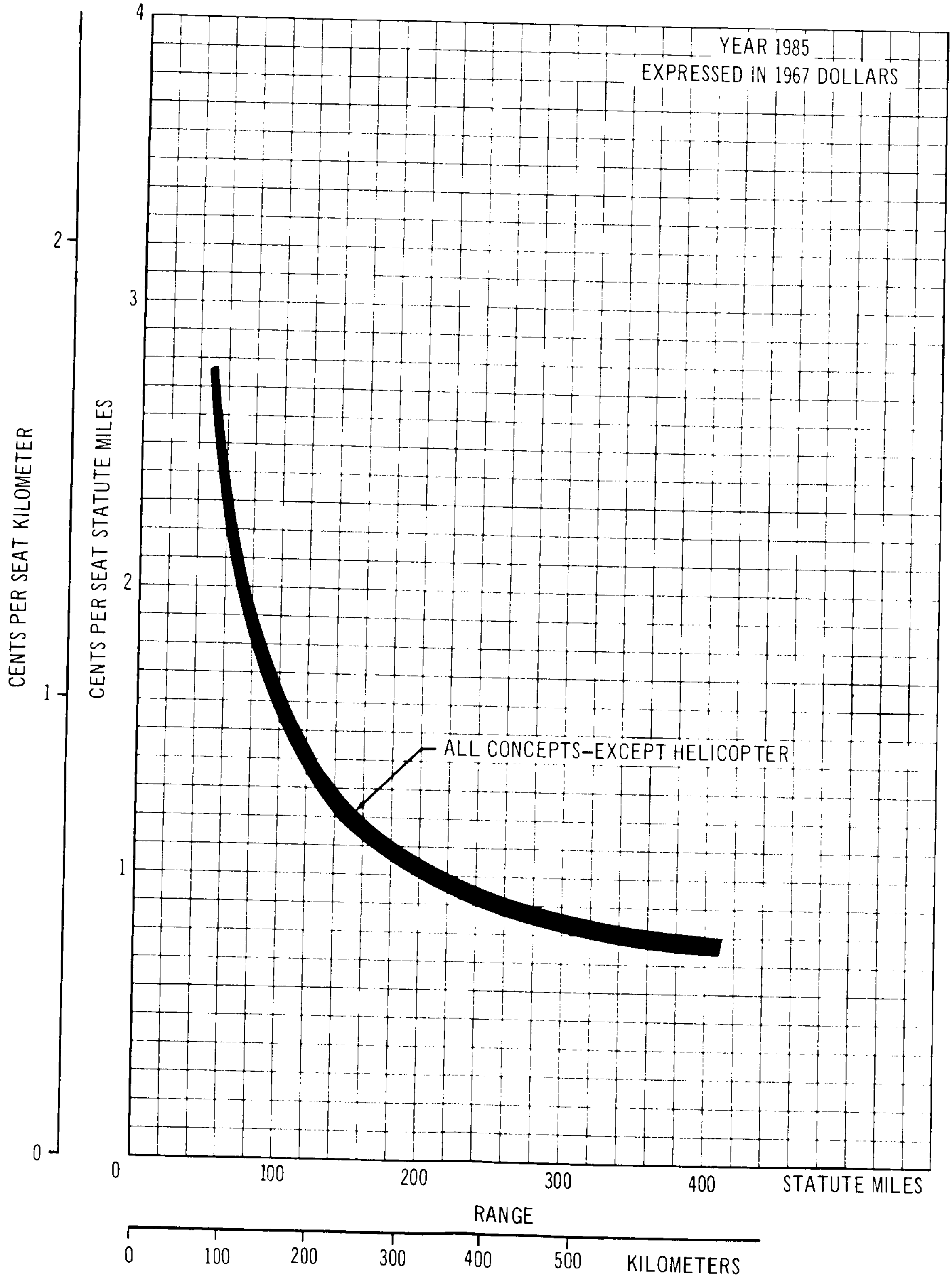


Figure 23: Indirect Operating Cost—120- Passenger Capacity, Reduced Facilities Depreciation

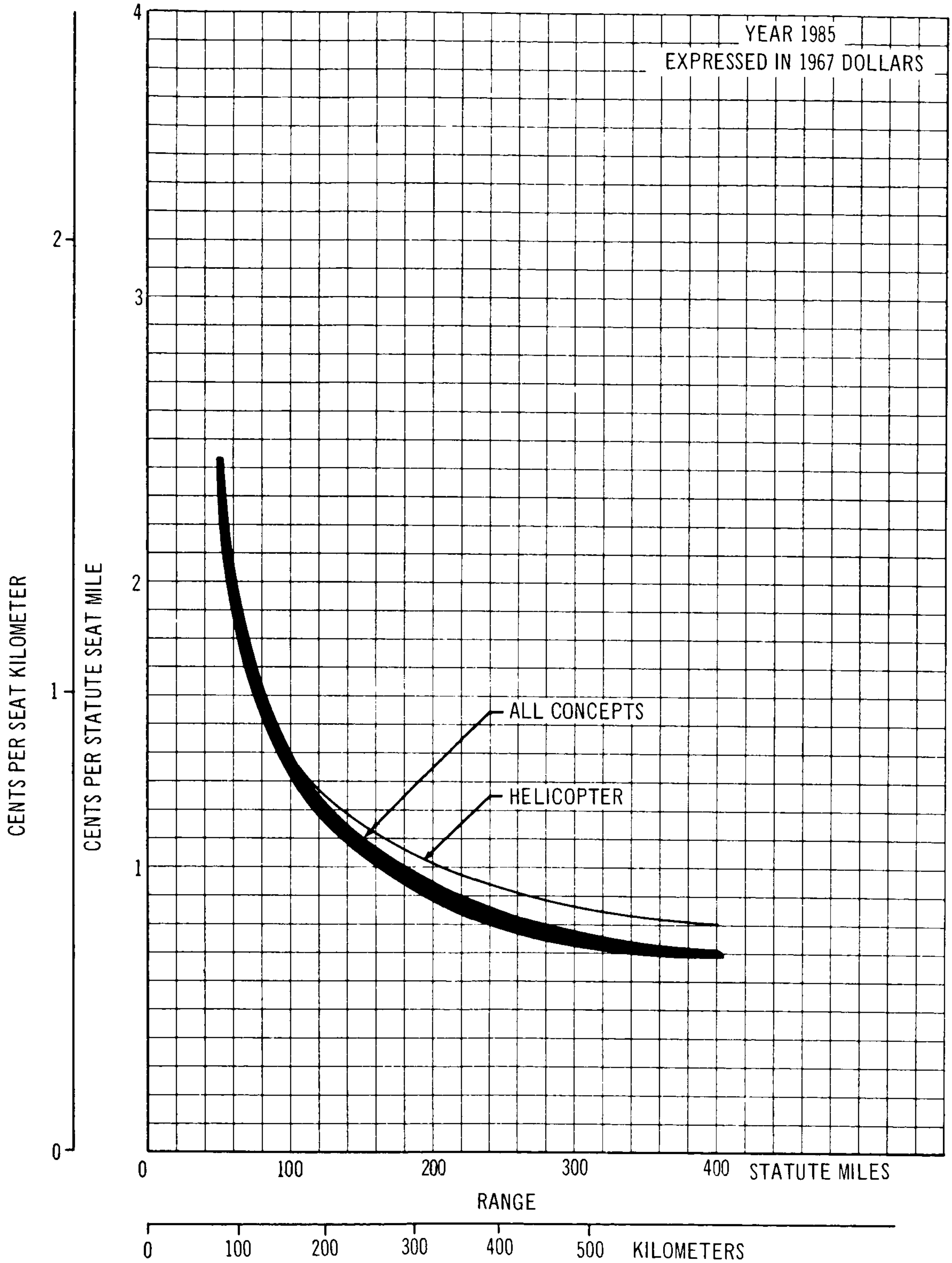


Figure 24: Indirect Operating Cost—200-Passenger Capacity, Reduced Facilities Depreciation

6.5 Vehicle Profitability

Fare levels. — The combination of the revenue side of the operation with the total operating cost provides visibility to the profitability of each of the concepts at any range. In establishing the revenue philosophy, the first step was to define the fare levels of the conventional airplane system considered operating as a major competitor to the V/STOL system.

It was recognized that very possibly by the 1985 time period, 200- and even 500-passenger, short-haul, high-density, conventional (CTOL) aircraft would be operating in the Northeast and on the West Coast and possibly the Gulf Coast, but in the latter case a size between 100 and 200 seats was considered more likely. Consequently, two levels of base fare, representative of CTOL operations, are postulated for 1985 and are to be considered as ranging the possibilities that could exist in these three regions (see fig. 25).

The base fare used for the Northeast and West Coast regions is the average of the fares which produced a 15% return on sales after taxes at all ranges at a 60% load factor for the 200- and 500-seat low maneuver time CTOL. Due to the low-density market in the Gulf Coast region it was necessary to increase the fare to provide a profitable system operation. The base fare selected as appropriate was then a 15% return on sales for a 120-seat normal maneuver time CTOL.

In this study it is assumed that fare and yield are synonymous in that the system is defined to be self-supporting and does not offer any promotional or reduced rates. Initially, it was also recognized that the fare structure on the V/STOL systems could range from being equal to the CTOL level up to a premium level that would ensure the operator a maximum profit.

This increment in fare above the base can be considered as the amount a passenger is willing to pay if he values the time he saves by travelling faster (potentially the V/STOL way). It can also be considered as a difference in access cost in getting to and from the respective terminals, so that the total trip costs by any mode (VTOL, STOL, or CTOL) are identical. It can even be considered an increment that a customer is willing to pay for the added convenience of a nearby transport system whether it saves him time or not.

In view of the great disparity in establishing a universally accepted value of time* and the difficulty in defining quantitatively the latter consideration, it was generally established that the V/STOL fare level would be generated from the base CTOL level by the addition of an increment numerically equal to the difference in total access cost, and thus establish a condition of concept comparison on the basis of customer indifference to total trip costs. (This V/STOL fare level is sometimes referred to as the indifference fare level.) Trip cost and trip time plotted against range are shown in fig. 27 through 29.

*Values of time effects are studied in a sensitivity analysis (sec. 7.2.3.10.1).

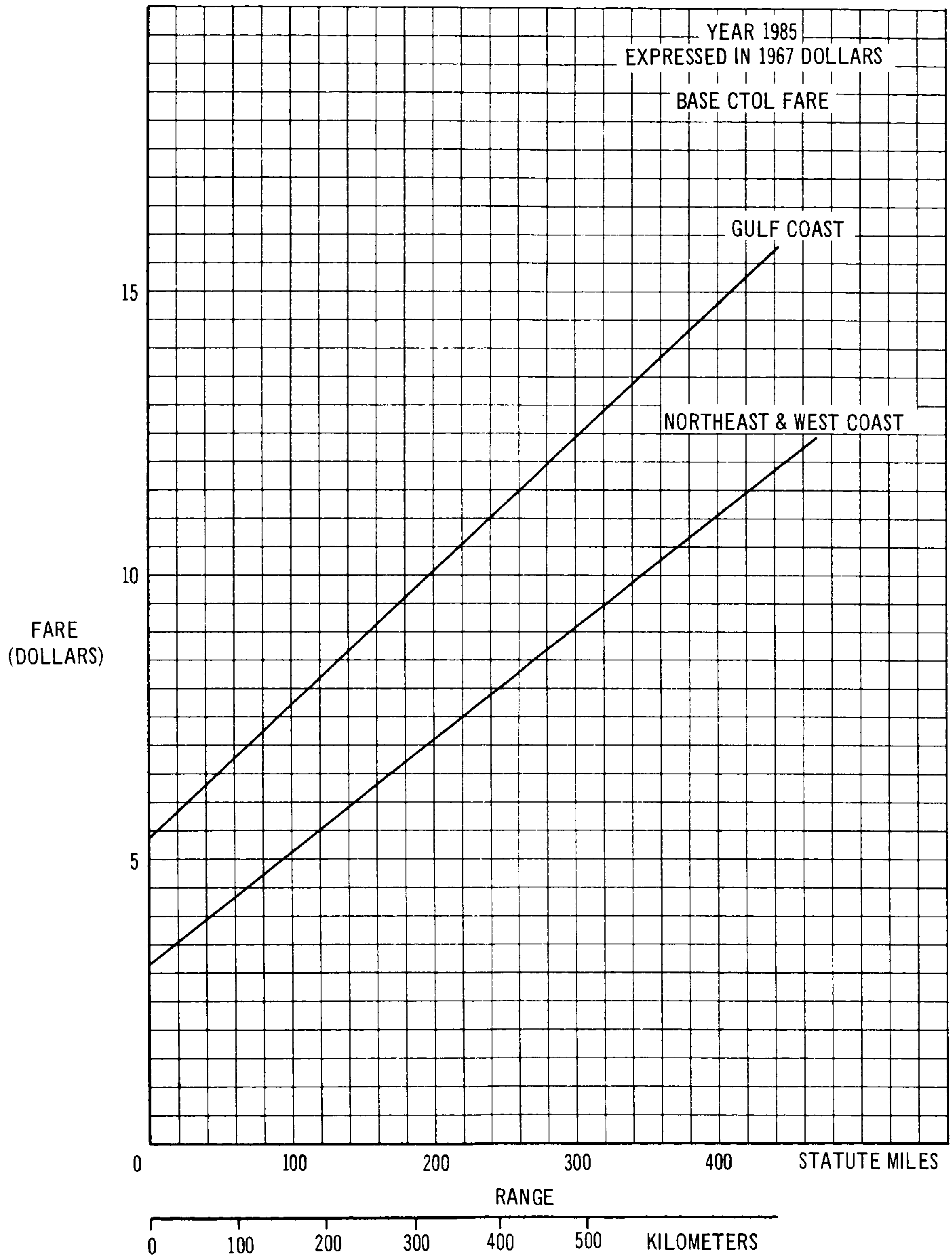


Figure 25: Conventional Airplane Base Fare—1985

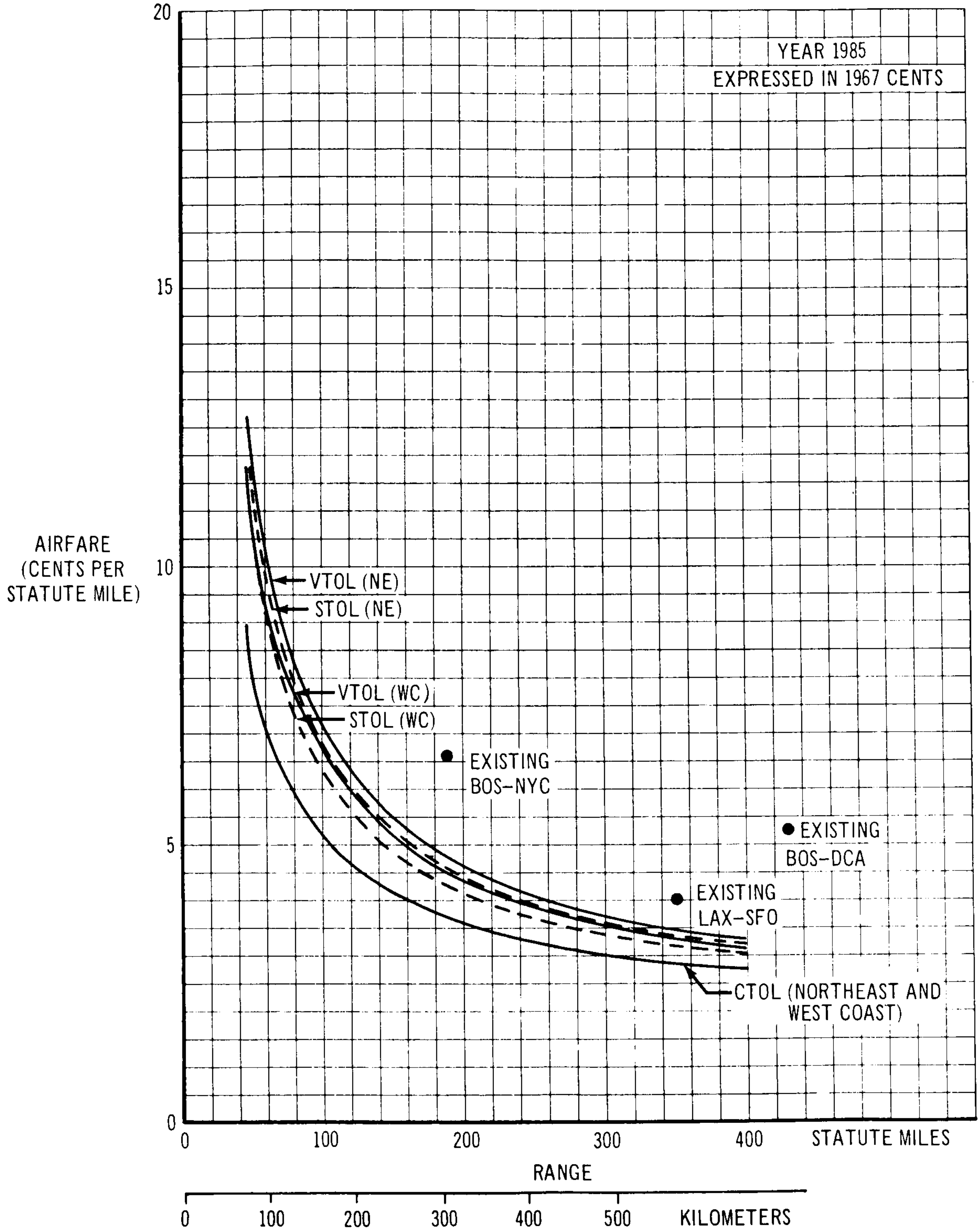


Figure 26: Per Mile Air Fare Rates—1985

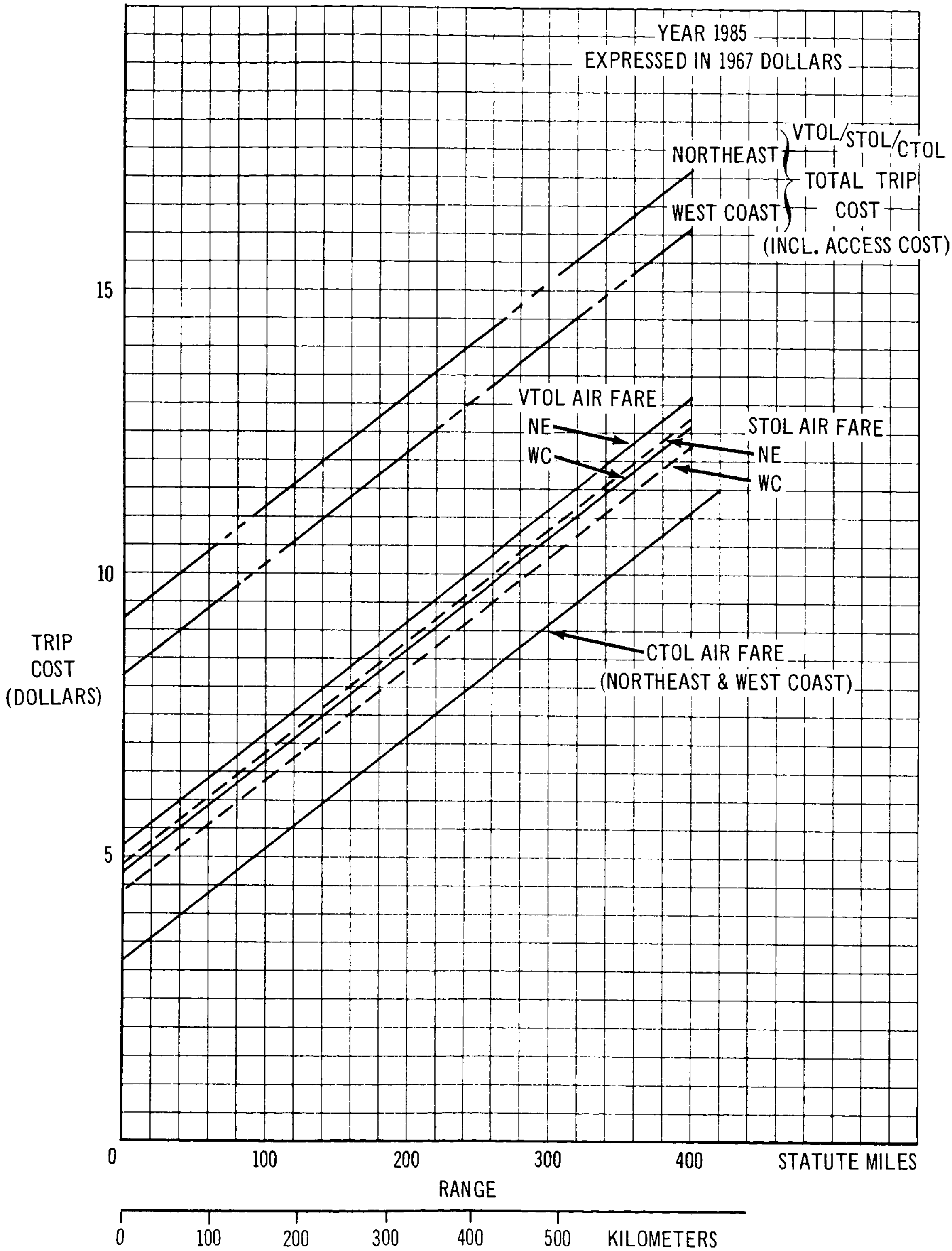


Figure 27: Trip Cost—Northeast and West Coast

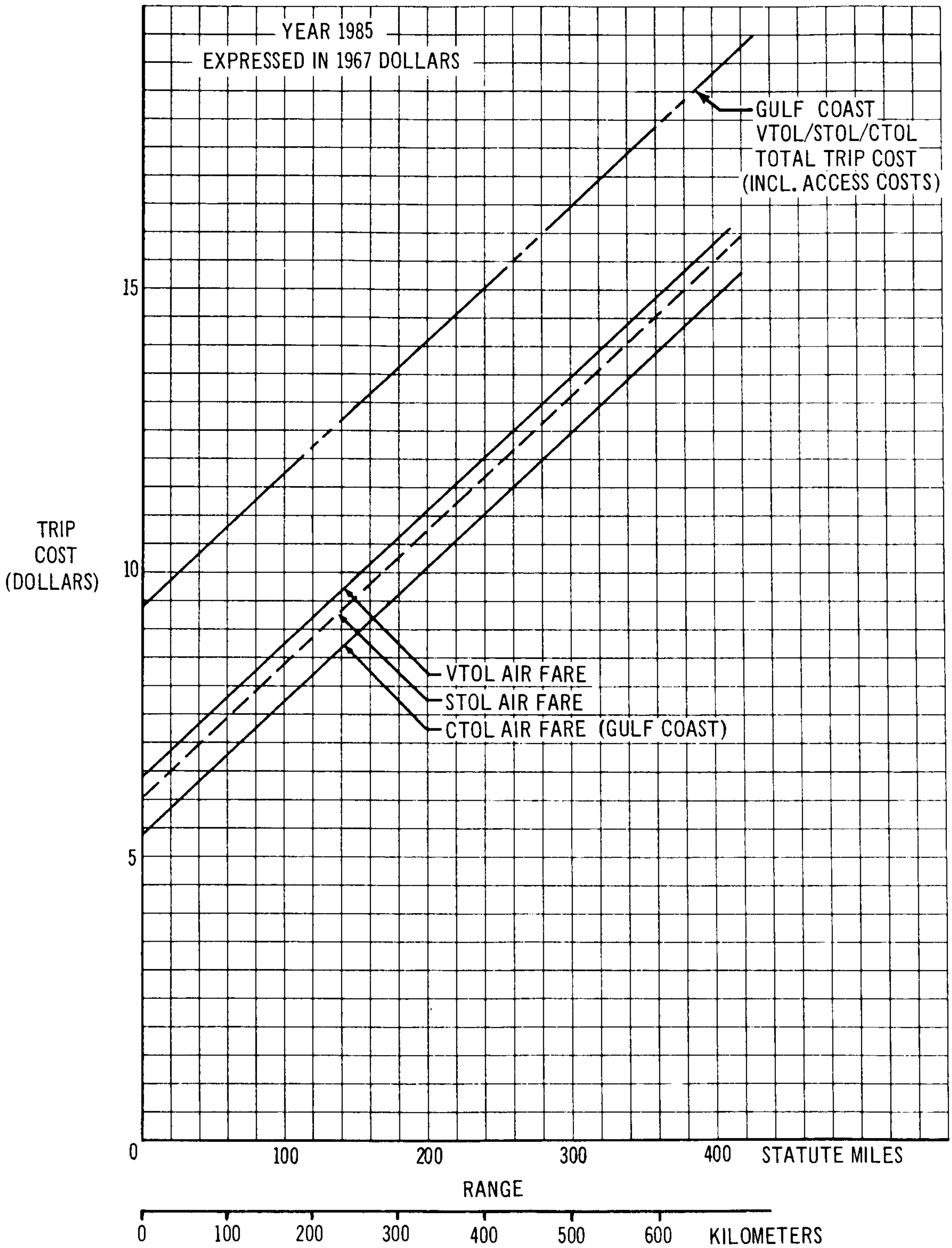


Figure 28: Trip Cost—Gulf Coast

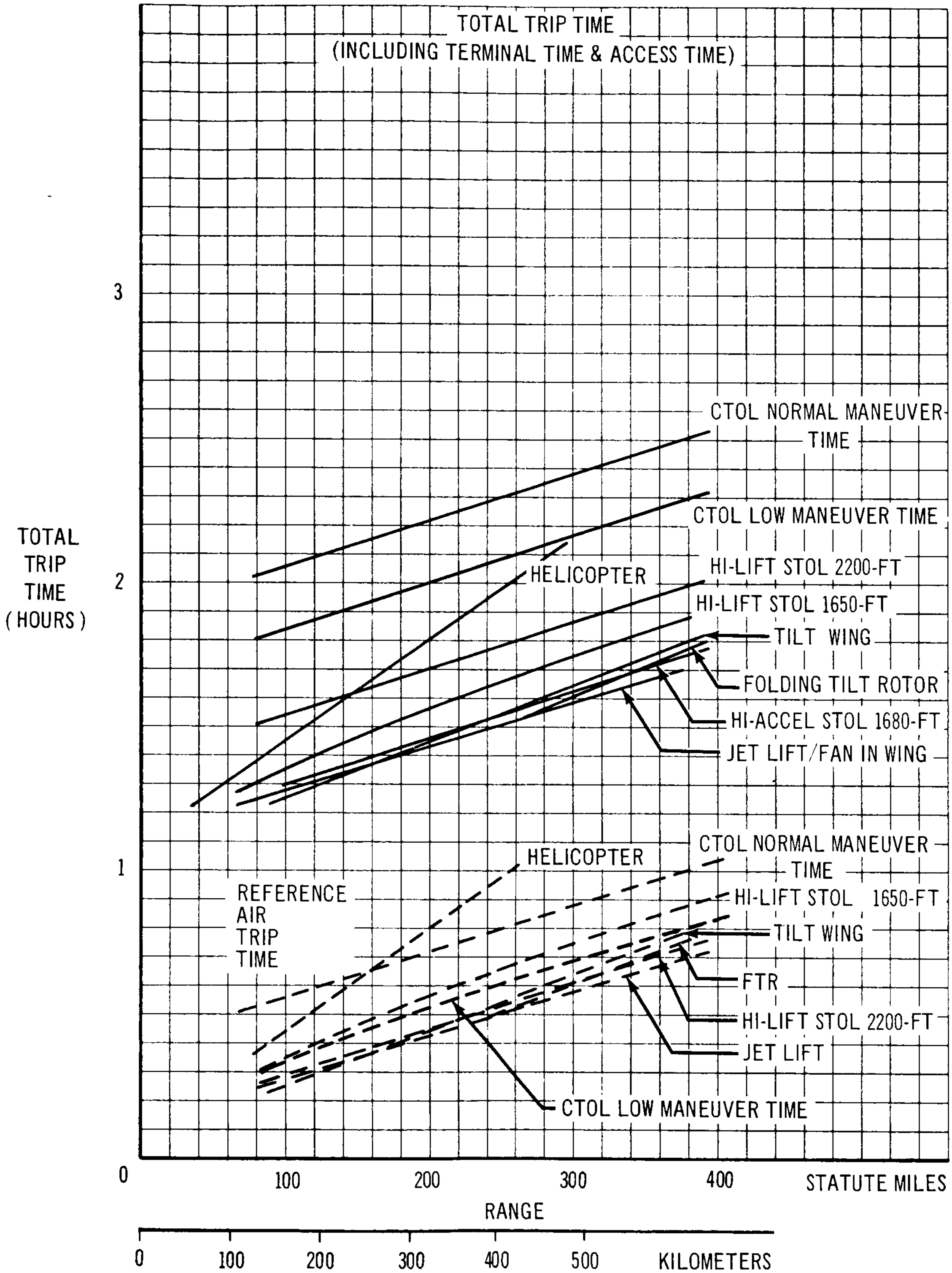


Figure 29: Total Trip Time—Northeast

Concept unit profitability. —The profitability criterion selected for the study is a return on sales measure where this is defined as the book profit per passenger divided by the yield per passenger or book profit as a percent of sales. It is calculated after taxes and investment credits are assessed.

For the purpose of tax calculations a 7-year shield is assumed, and the return on sales is estimated as the average per year over the 7-year period. It is calculated and plotted against range for a variety of assumptions of fare, indirect operating cost level, geographical region, and airplane design capacity (see figs. 30 to 38). A constant load factor of 60% is used. Consideration of these plots should indicate which concepts are the most profitable and at which ranges this profit accrues. As can be seen, however, while this is generally evident with respect to groups of concepts (as in the case of DOC's), discerning between specific concepts is still subject to the doubt of its usefulness in view of the small differences between concepts.

The rotor group (excluding the helicopter) returns the highest book profit at the shorter ranges for all sizes of V/STOL aircraft studied in each geographical region at all fare levels. The 2000-ft, high-lift STOL and the non-rotor V/STOL group showed the highest profit at the longer ranges. Of particular importance, however, is the relationship of the V/STOL groups with respect to the CTOL concepts with both low and normal maneuver times. These latter concepts represent the competition to the V/STOL concepts.

In figs. 30 and 31 where the V/STOL fare is generated from a CTOL base that is itself derived from a return on sales of an aircraft larger than 200 seats, the V/STOL groups at the 200-passenger capacity are generally more profitable than the CTOL concepts. Note that the return on sales for a 200-seat CTOL low maneuver time aircraft is approximately 12%. However, in figs 33 and 34, the V/STOL groups at 120-passenger capacity deteriorate relative to one of the CTOL concepts except at the very short ranges. This is representative of the Northeast and West Coast regions, where the CTOL fare is based on the aircraft with a capacity greater than 200. On the Gulf Coast, where the CTOL fare is based on a 120-passenger airplane, profitability shows the same reducing trend with decreasing size, but at the smallest size it does not become marginally positive. (see figs. 32, 35 and 38.)

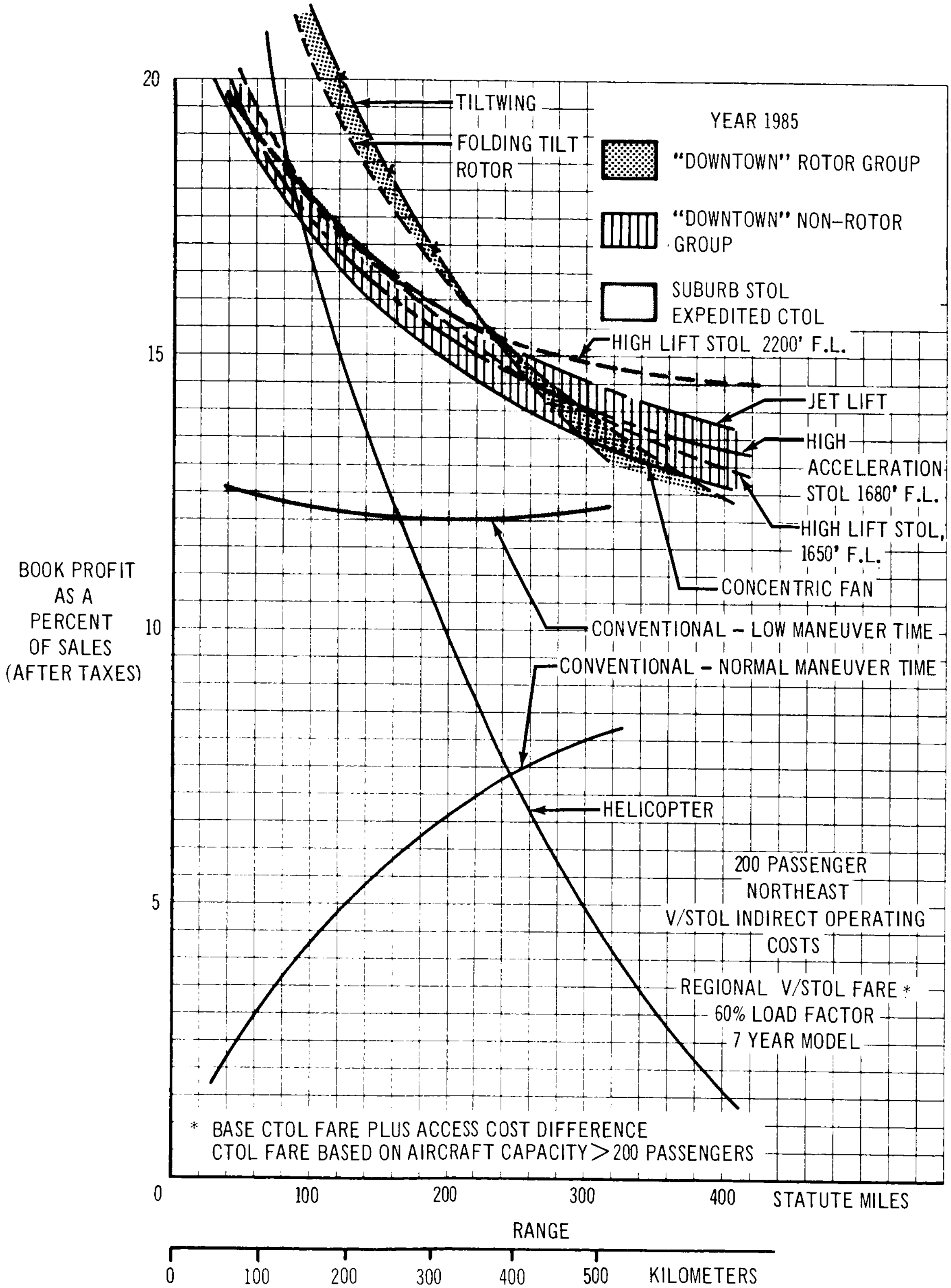


Figure 30: Return on Sales—Northeast, 200-Passenger Capacity V/STOL Fare at Indifference Level

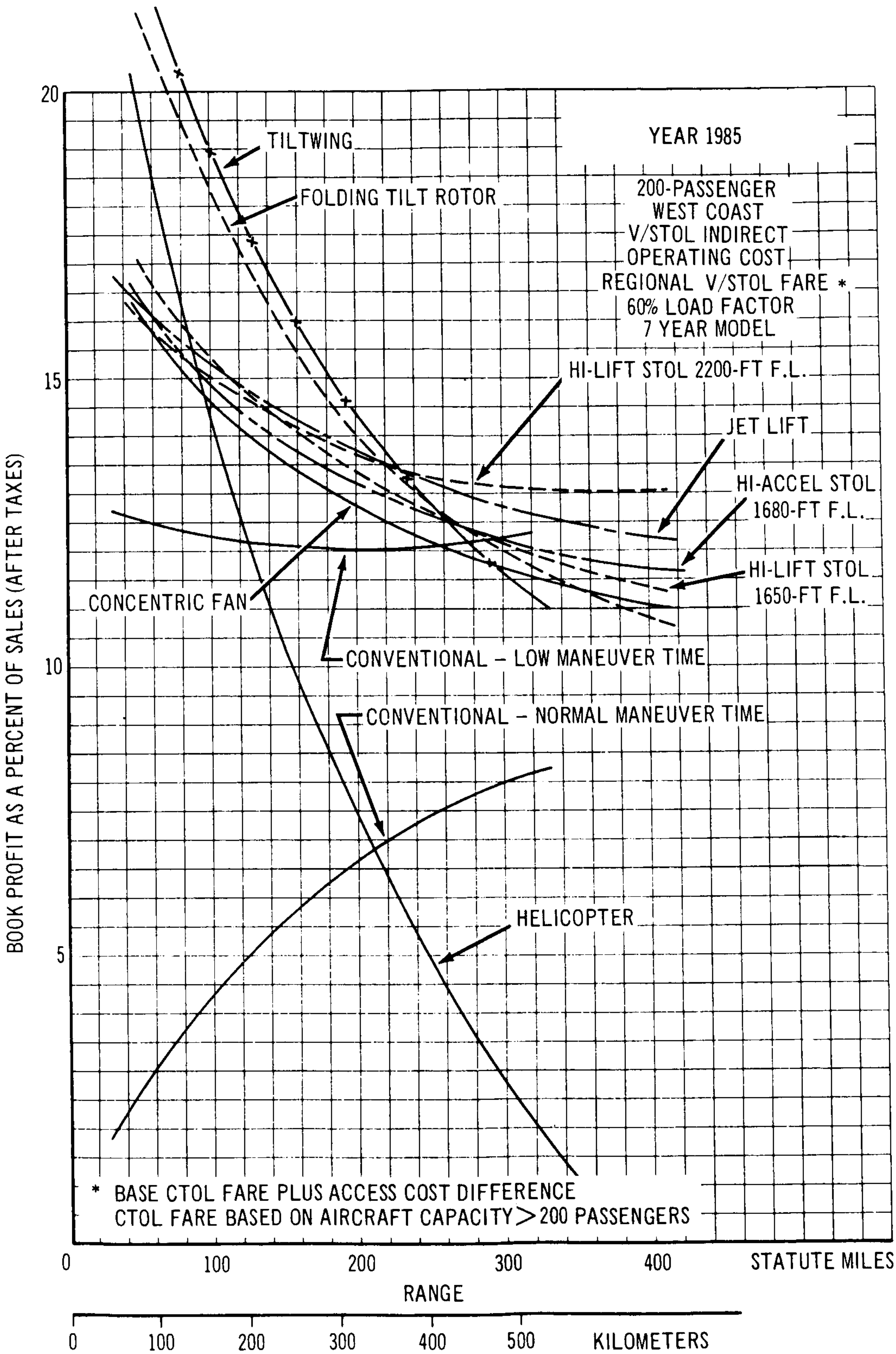


Figure 31: Return on Sales—West Coast, 200-Passenger Capacity V/STOL Fare at Indifference Level

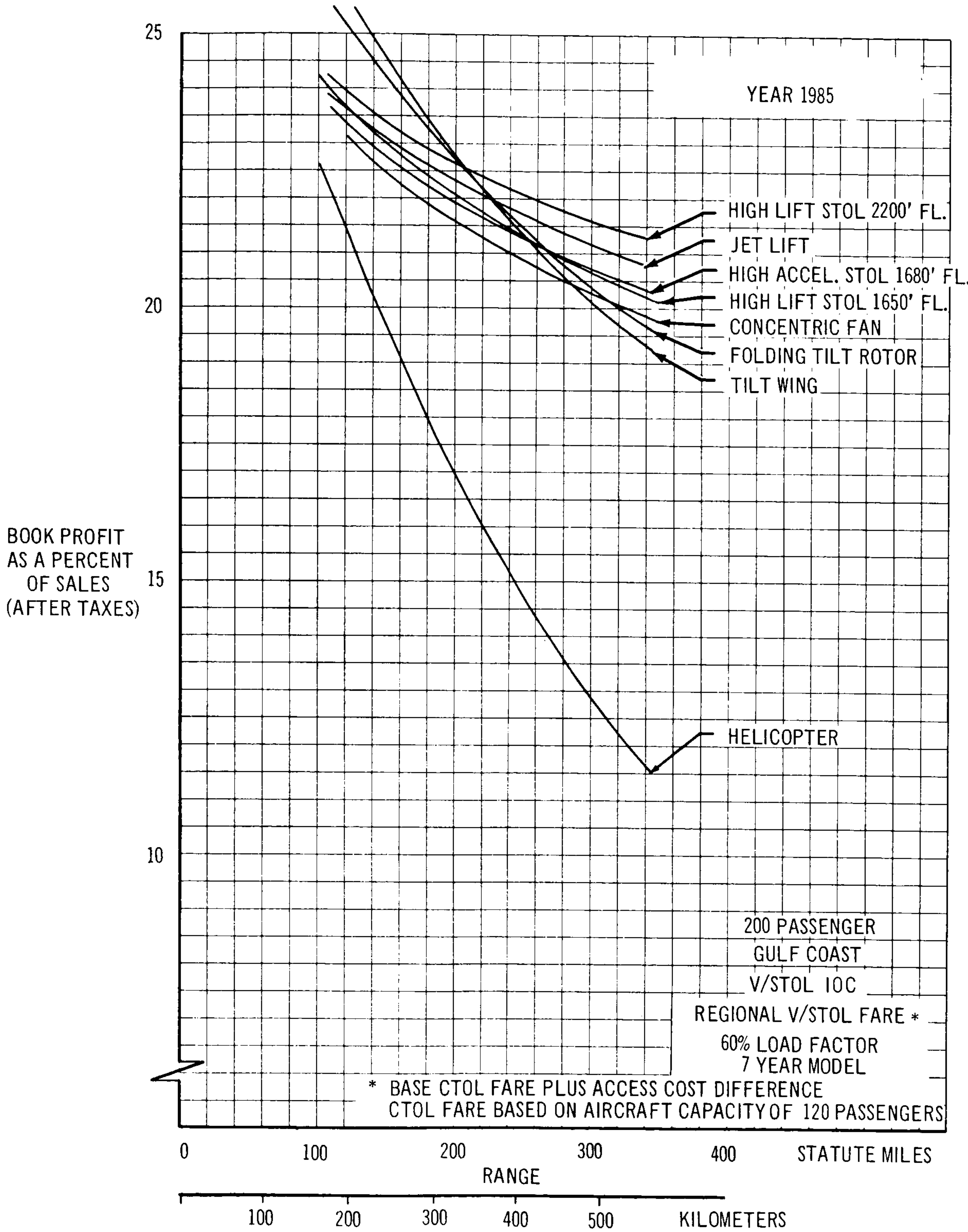


Figure 32: Return on Sales—Gulf Coast, 200-Passenger Capacity V/STOL Fare at Indifference Level

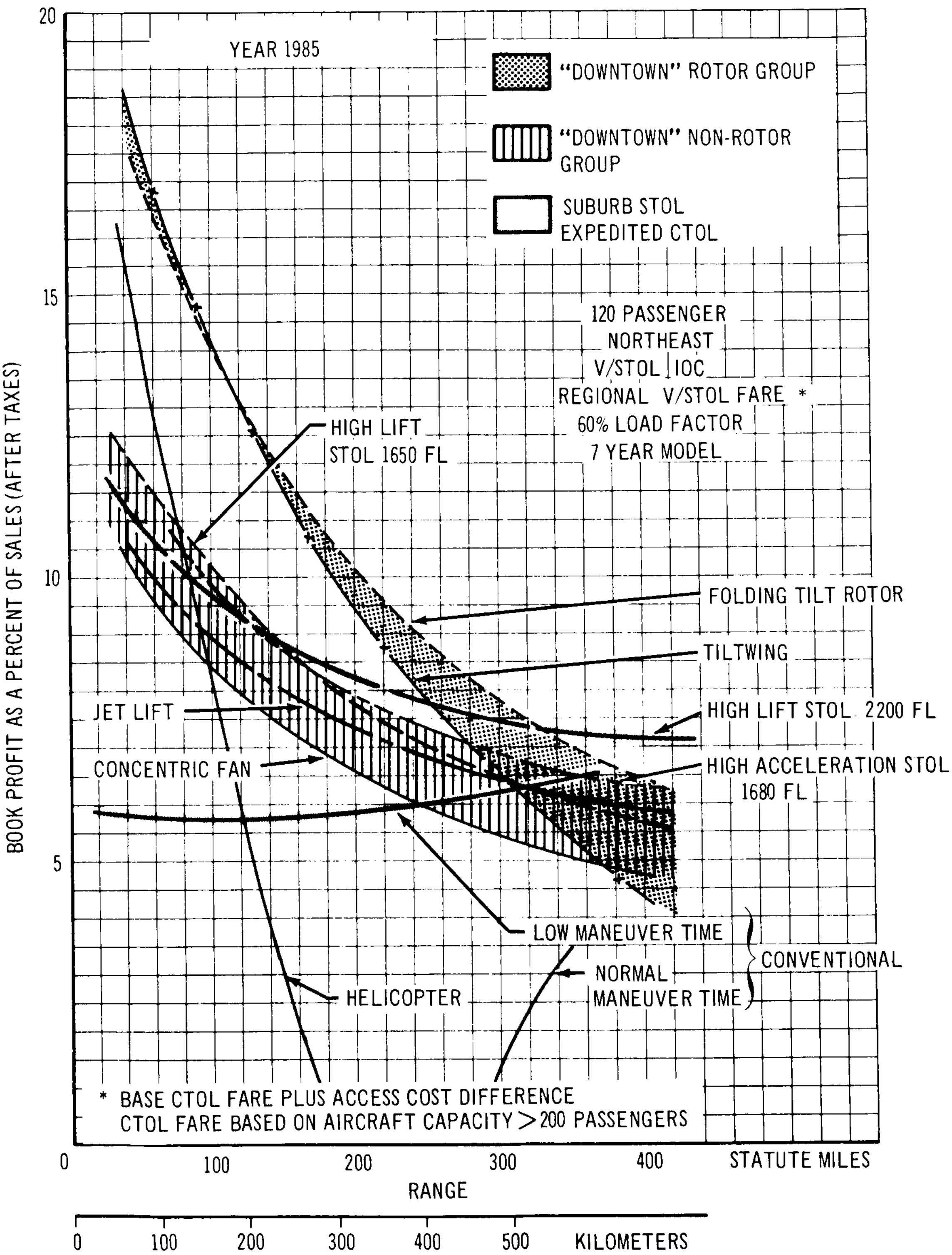


Figure 33: Return on Sales—Northeast, 120-Passenger Capacity V/STOL Fare at Indifference Level

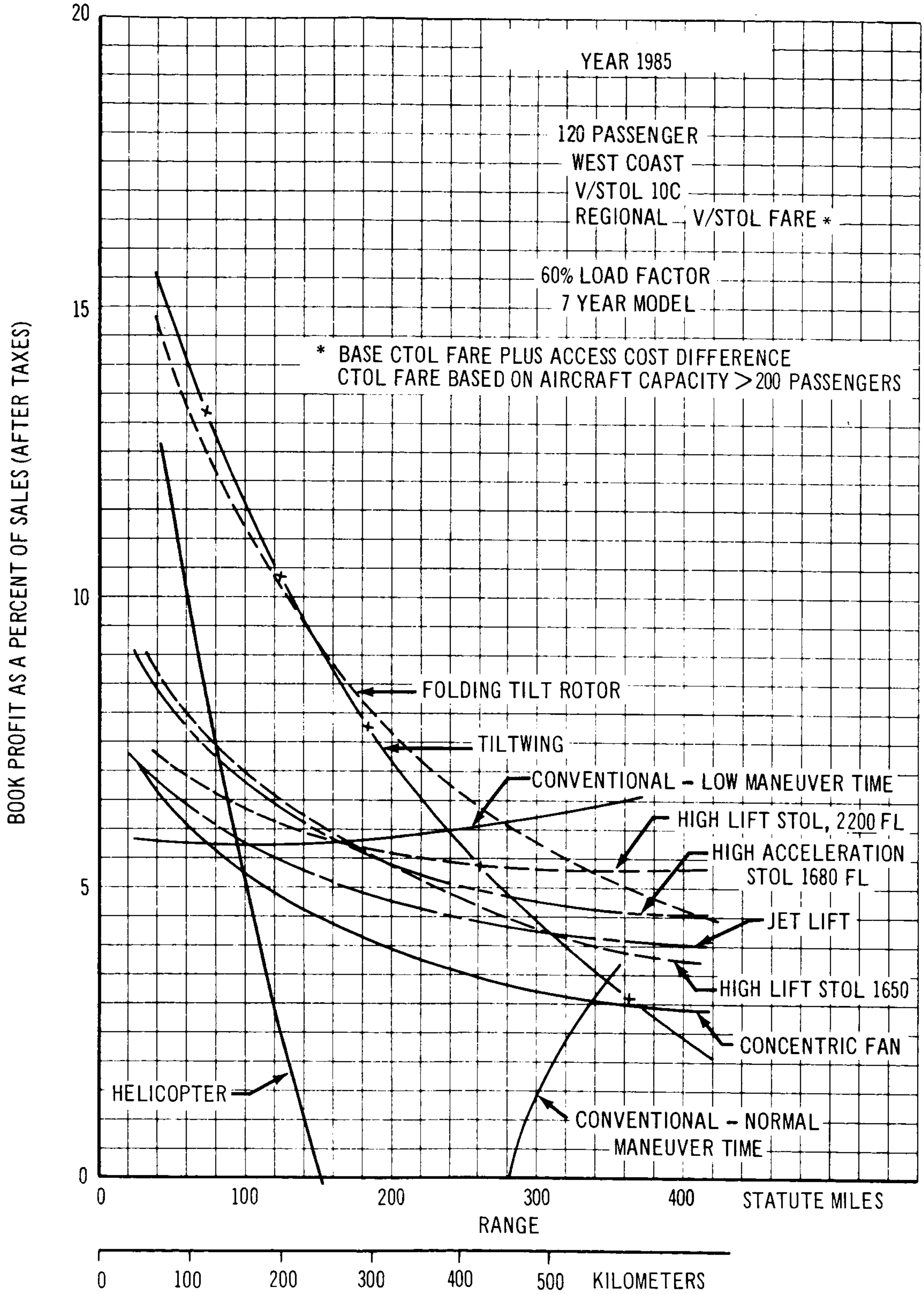


Figure 34: Return on Sales—West Coast, 120-Passenger Capacity V/STOL Fare at Indifference Level

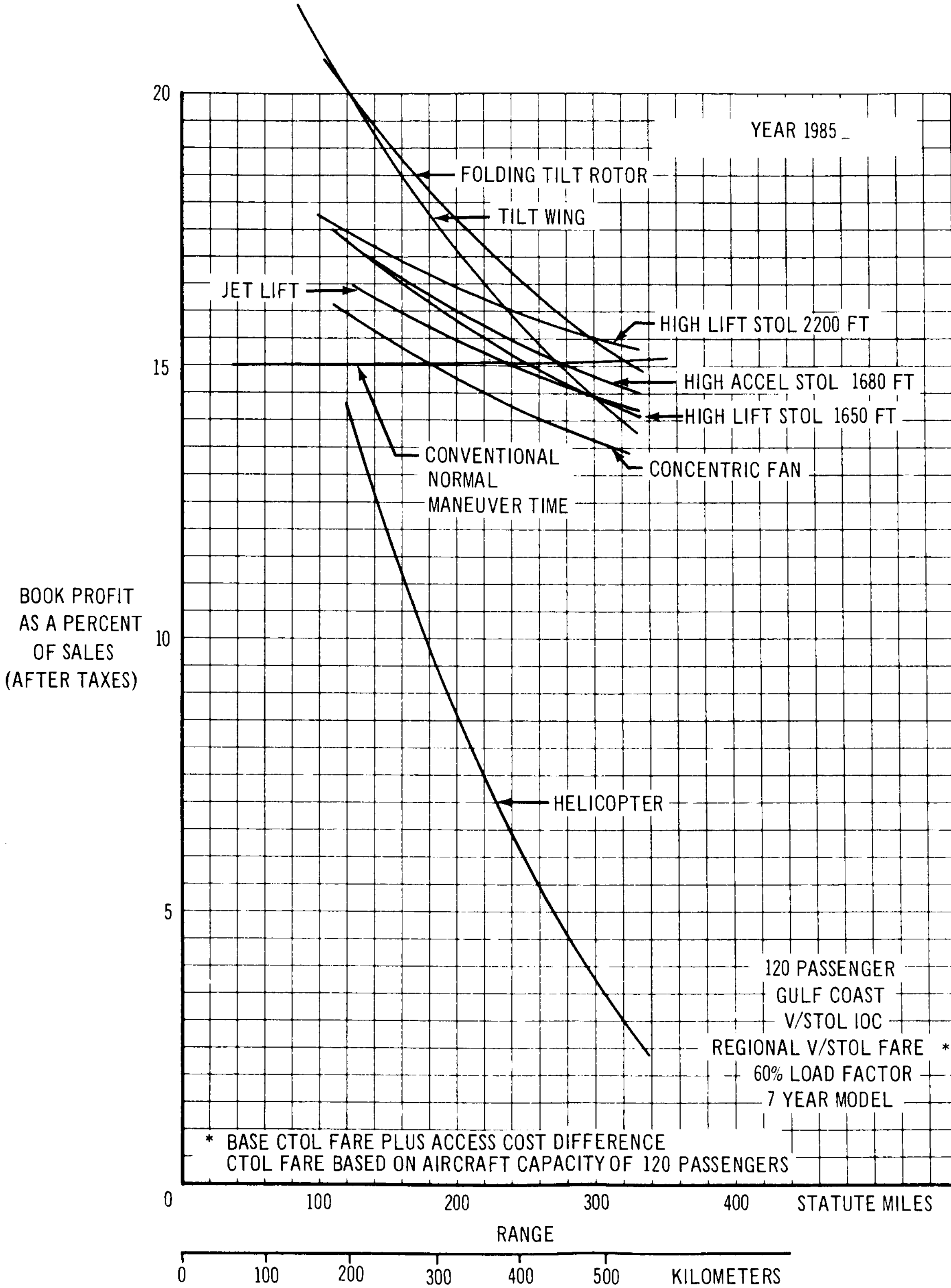


Figure 35: Return on Sales—Gulf Coast, 120-Passenger Capacity V/STOL Fare at Indifference Level

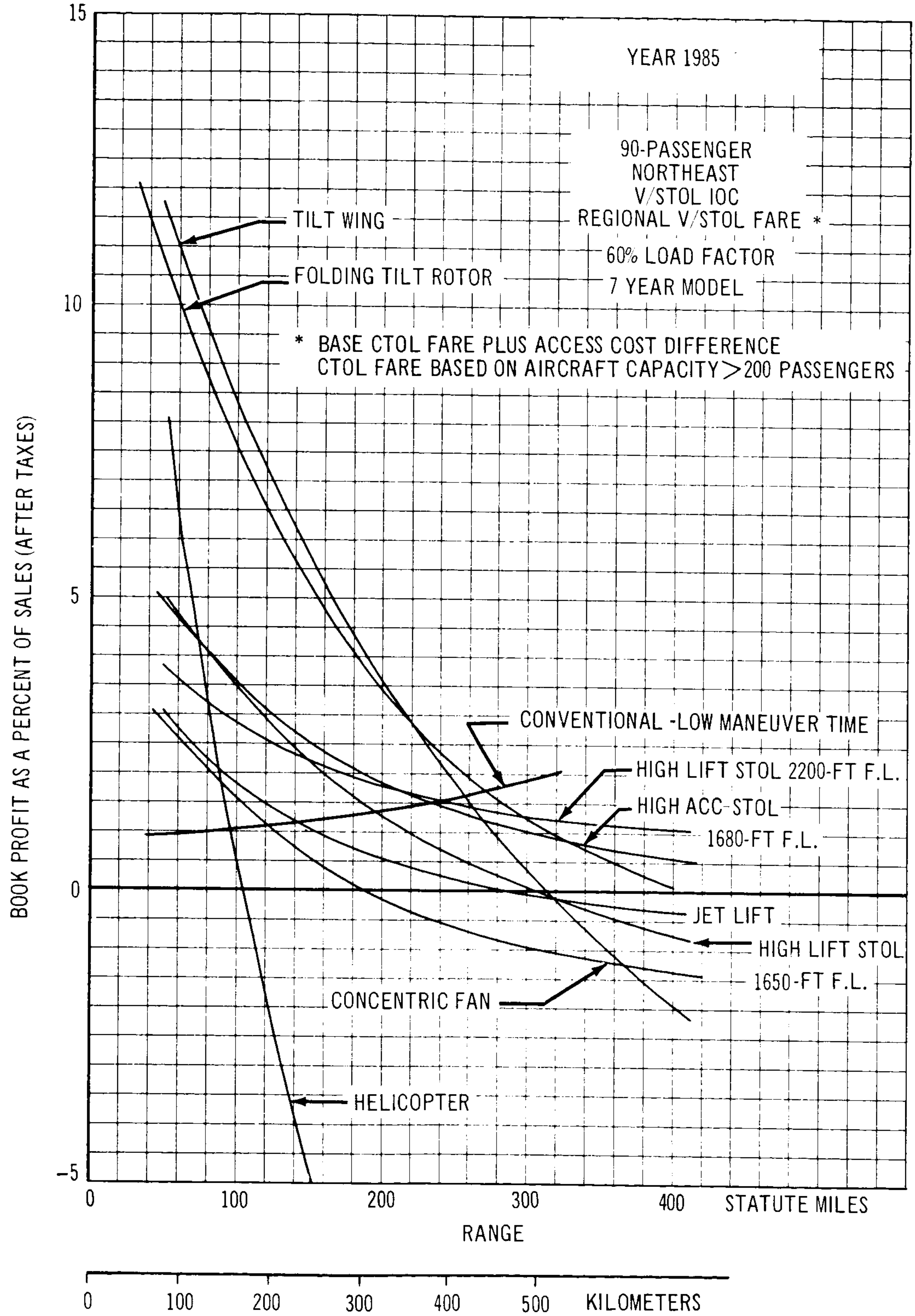


Figure 36: Return on Sales—Northeast, 90-Passenger Capacity V/STOL Fare at Indifference Level

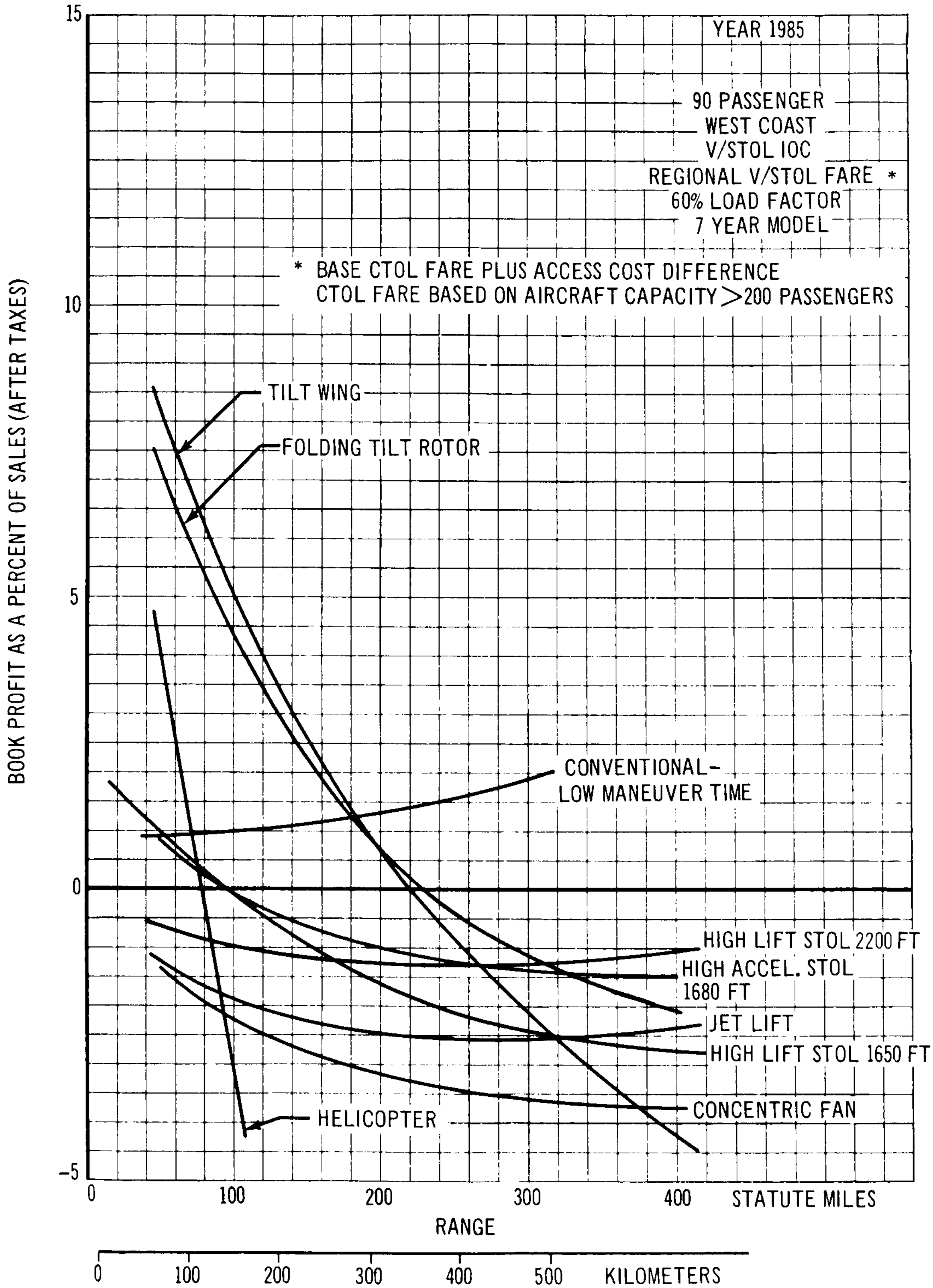


Figure 37: Return on Sales—West Coast, 90-Passenger Capacity V/STOL Fare at Indifference Level

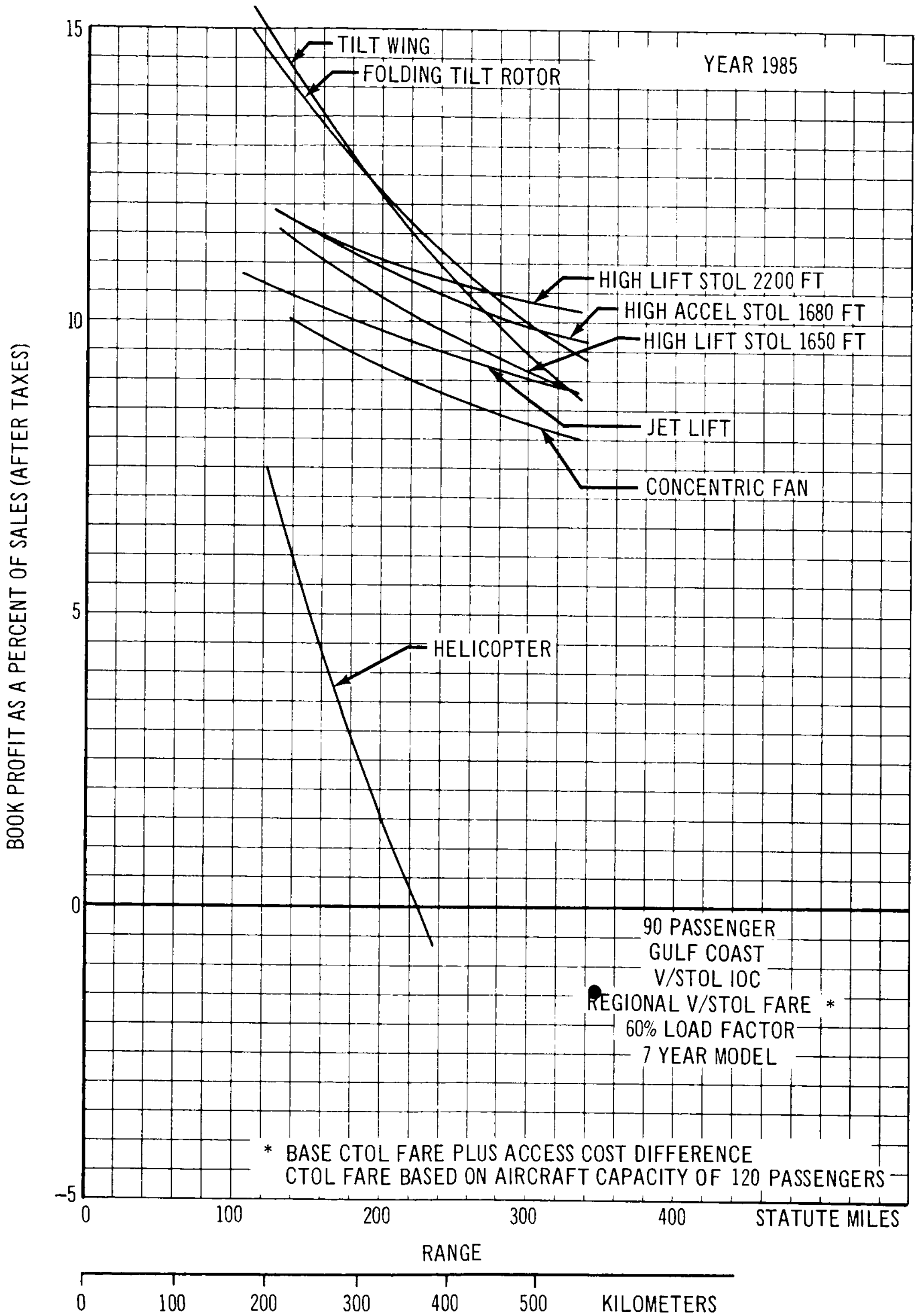


Figure 38: Return on Sales—Gulf Coast, 90-Passenger Capacity V/STOL Fare at Indifference Level

These trends emphasize the point that each geographical region justifies its own base CTOL fare level so that when the premium charge is added to obtain the V/STOL fare (this incremental charge being smallest on the Gulf Coast and largest in the Northeast) the V/STOL concepts can still obtain a favorable profit position relative to the CTOL concepts. Later it is shown that this requirement of individual fare levels for each region is strengthened by the fact that the relatively lower total traffic demand of the West Coast and Gulf Coast may not generate a practical level of profit after taxes unless a sufficiently high fare level is proposed.

One further point to consider is that shown in fig. 39 , where the profitability of the smaller V/STOL concepts is shown relative to the larger (200-passenger capacity) CTOL concepts. This situation could represent the Northeast situation of operating high-density CTOL designs against smaller V/STOL aircraft.

When the operator of the V/STOL system offers the same fare structure as the CTOL operator, the deterioration in the V/STOL vehicle profitability relative to the CTOL concepts is as shown in figs. 40 and 41.

At the shorter ranges the rotor concepts including the helicopter can be the most profitable if the only competition is a normal maneuver time CTOL concept, but if the low maneuver time CTOL concept is available then the V/STOL operator must recognize that he is using a vehicle that is not the most profitable. This does not imply, however, that he cannot make a profit, because his system can offer additional convenience and faster trips at a lower total trip cost, and hence can potentially attract a large market.

In the assessment of vehicle indirect operating costs (IOC), one of the factors to be considered is the depreciation cost of the ground facilities. In this study two assumptions are made concerning this cost. One, the basic assumption of private ownership of facilities and depreciation of full facilities cost (no subsidization). Second, the assumption that the facilities cost depreciation may be handled in the manner of the current conventional airplane facilities thereby giving reduced IOC levels.

The following vehicle profitability, figs. 42 and 43, show the effect of this reduced facilities depreciation charge. An increase in profitability of all V/STOL concepts is evident, with the STOL concepts benefiting the most from the reduction in IOC.

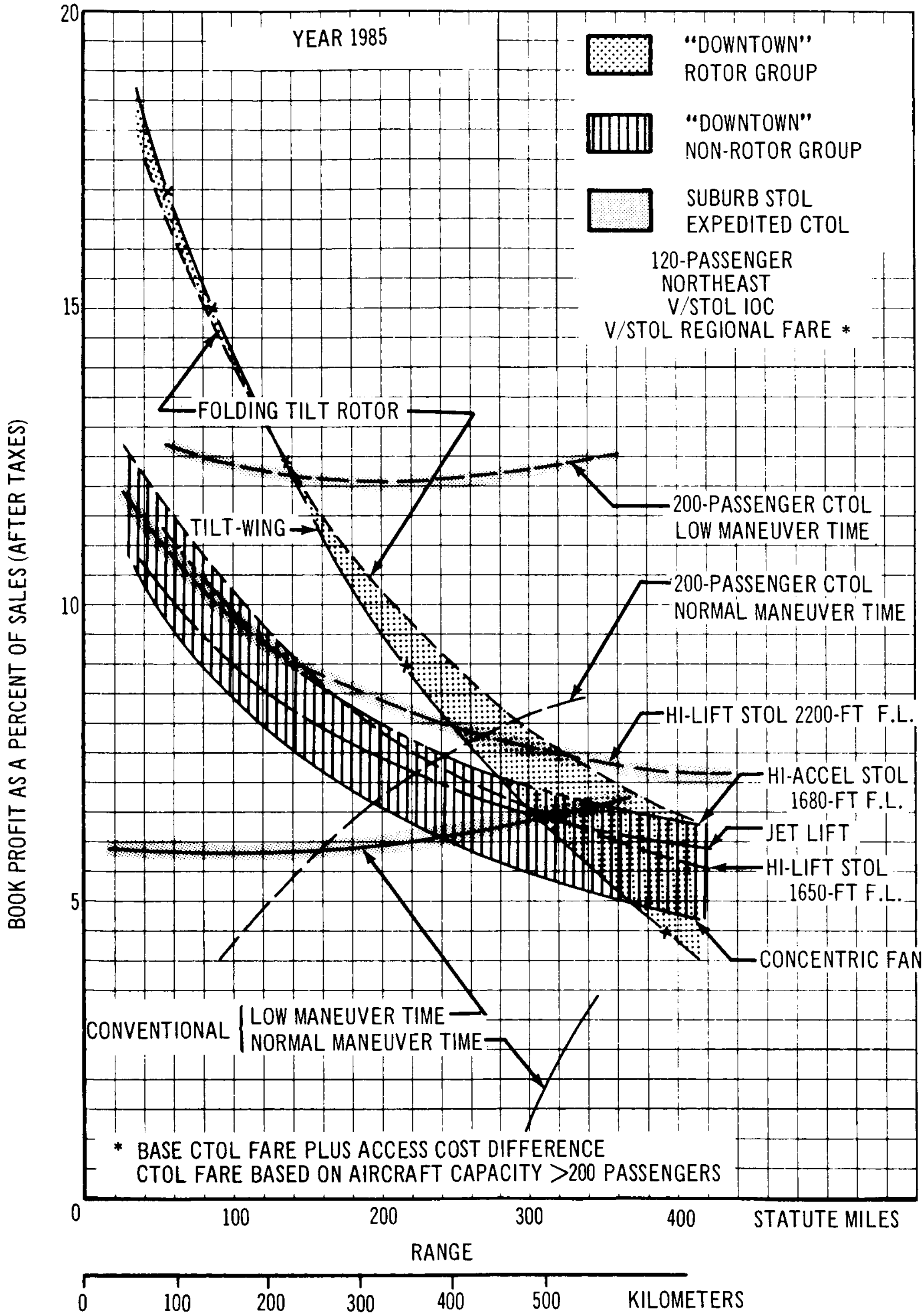


Figure 39: Return on Sales—120-Passenger Capacity V/STOL Concepts Compared With 200-Passenger Capacity CTOL

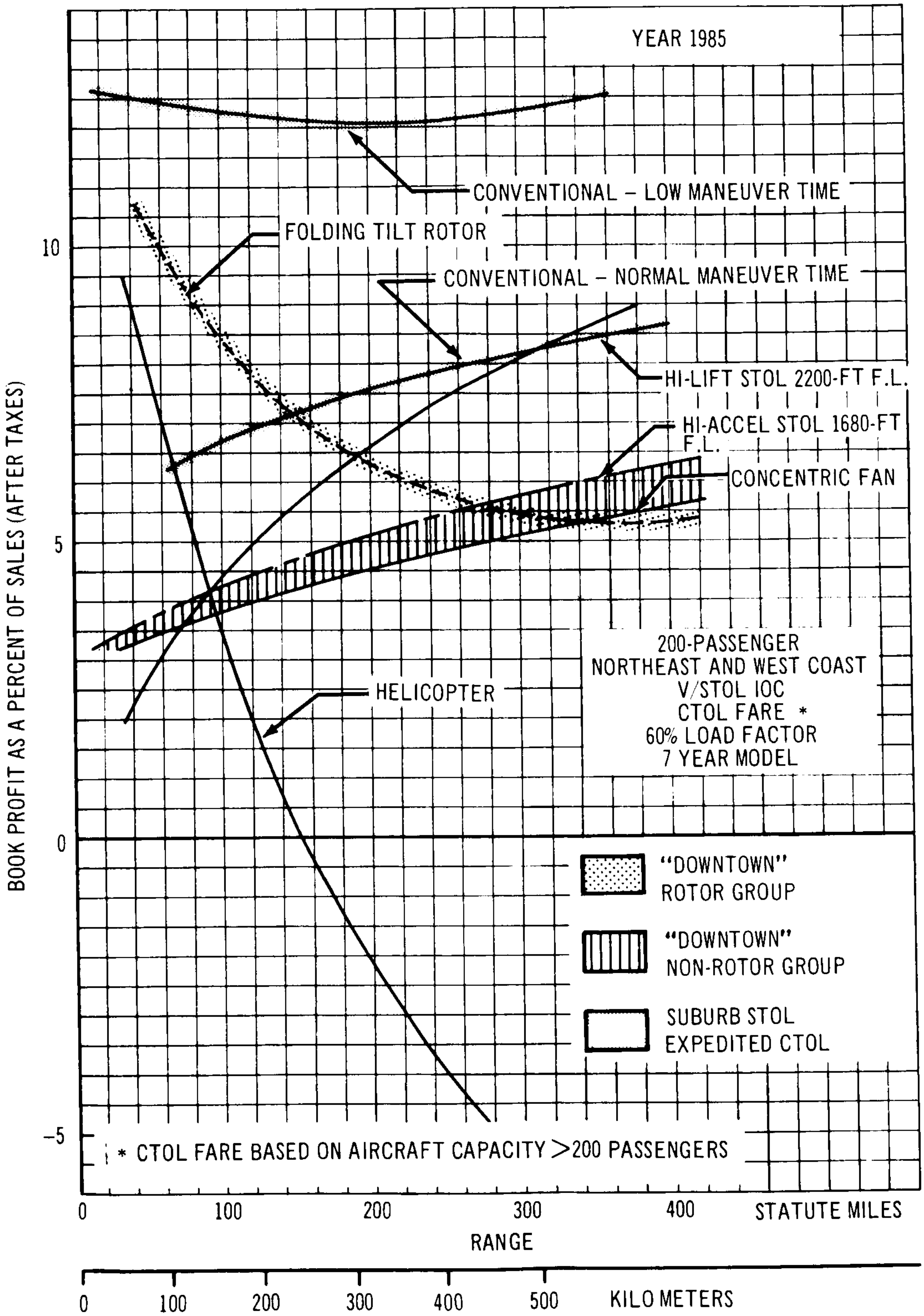


Figure 40: Return on Sales—Northeast and West Coast, 200-Passenger Capacity V/STOL Fare Reduced To CTOL Level

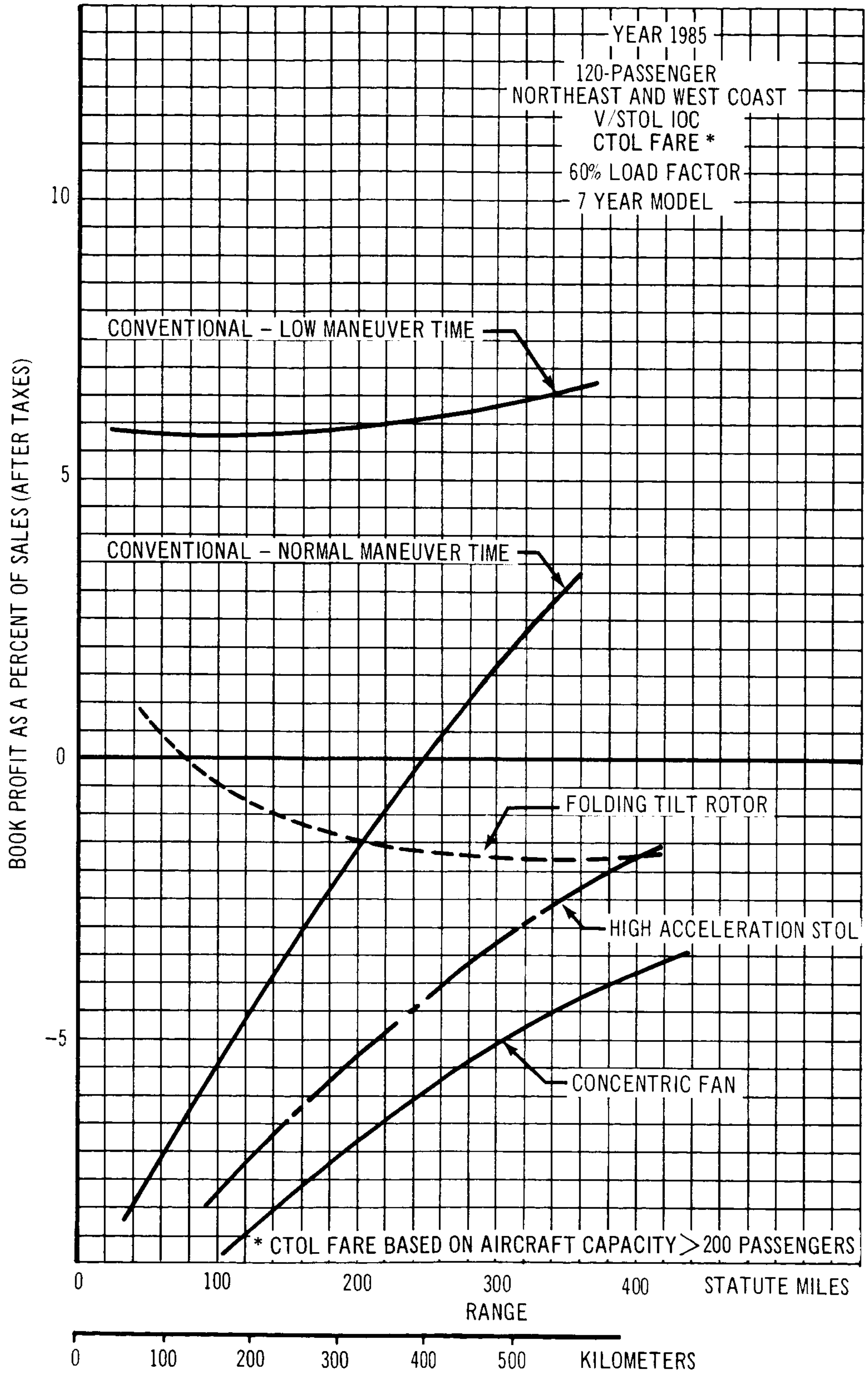


Figure 41: Return on Sales—Northeast and West Coast, 120-Passenger Capacity V/STOL Fare Reduced To CTOL Level

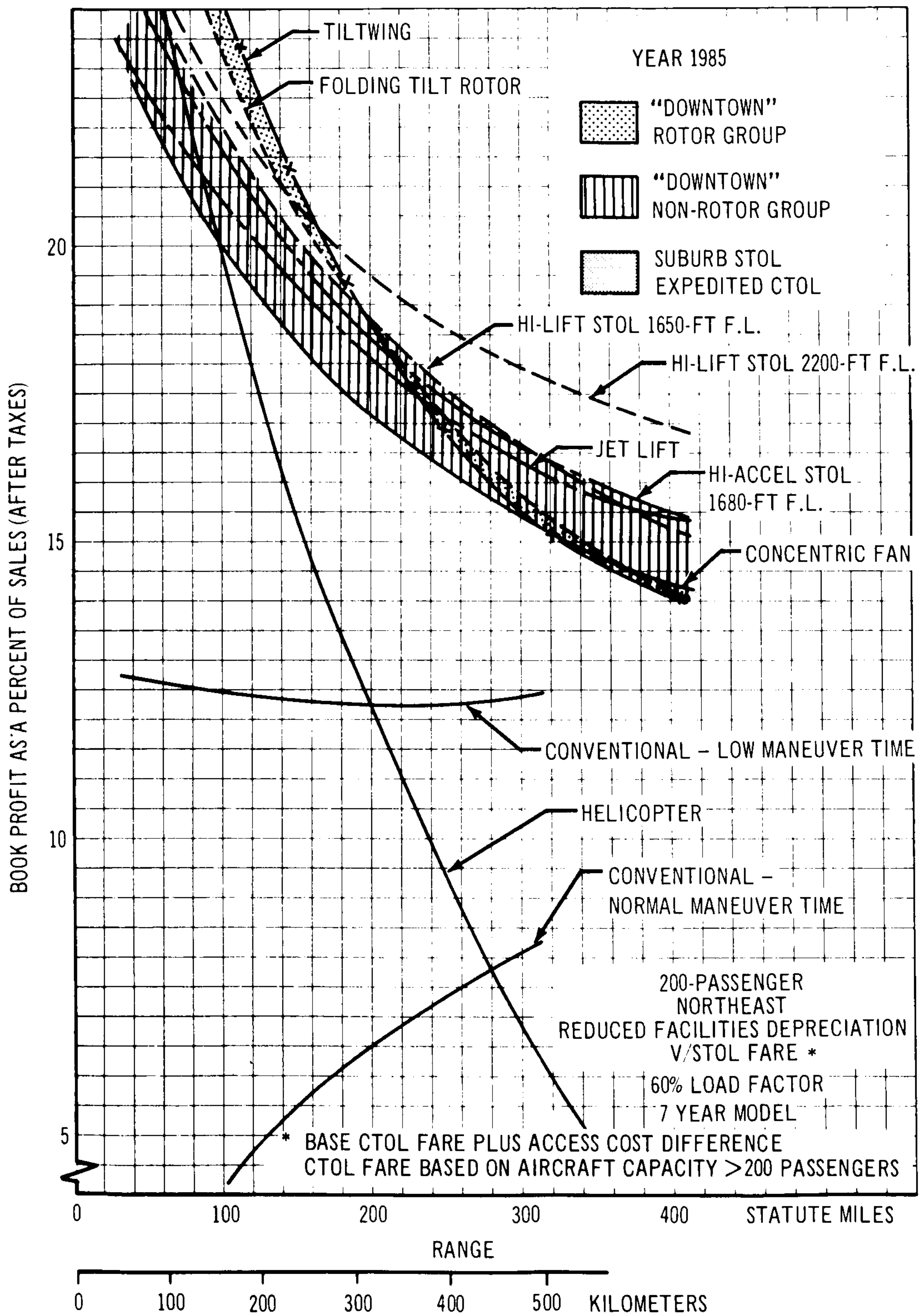


Figure 42: Return on Sales—Northeast, 200-Passenger Capacity, Reduced Facilities Depreciation

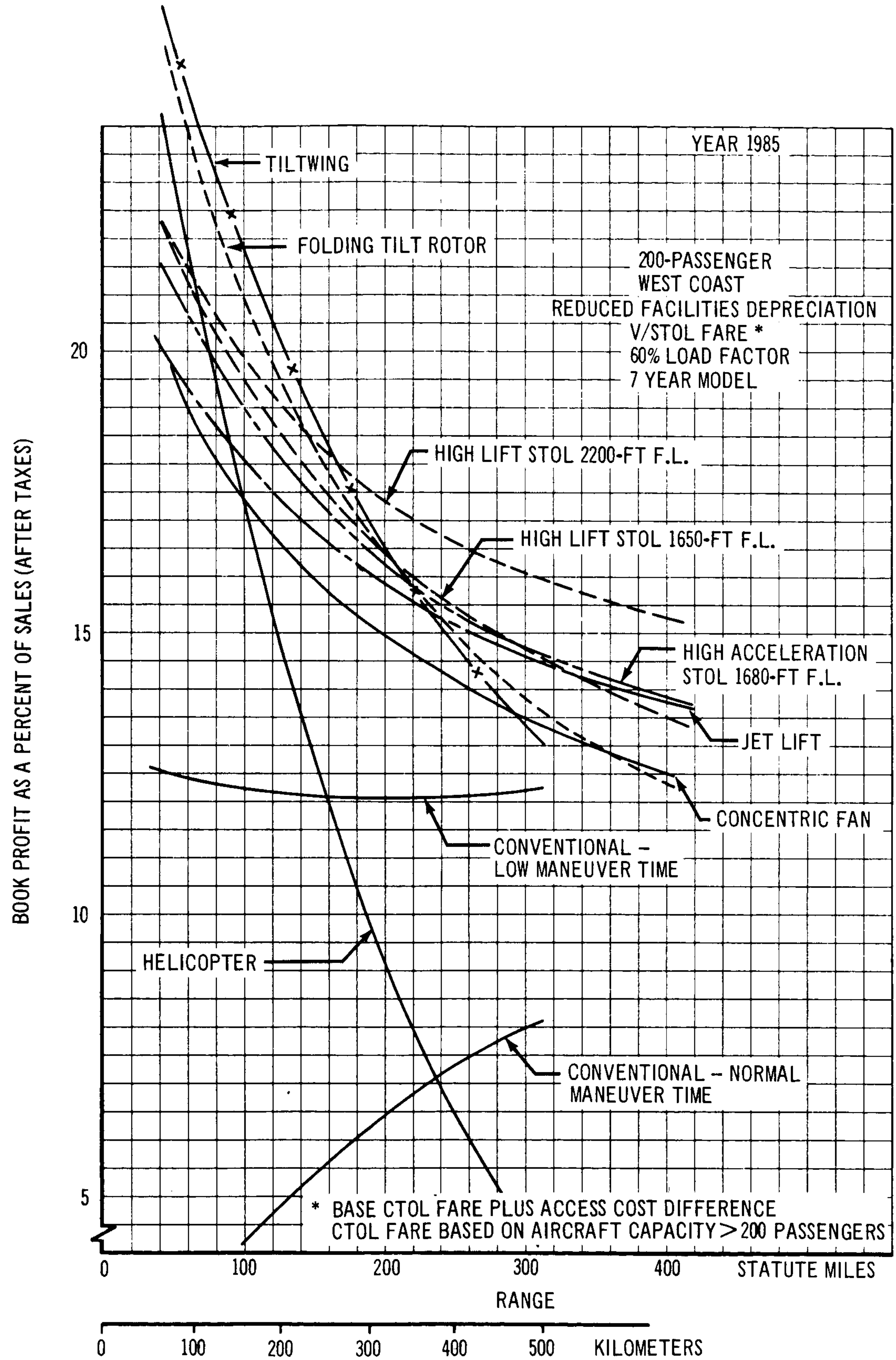


Figure 43: Return on Sales, West Coast—200-Passenger Capacity Reduced Facilities Depreciation

6.6 Systems Analysis and Concept Suitability

6.6.1 Economic suitability. —The combination of the unit profitability of the vehicle versus range with the passenger level and frequency demand of a specified airline system finally provides visibility in an economic sense to the suitability of any particular concept on a system-wide basis. Summaries of system operator profit are presented showing the relative economic suitability of each concept in each geographical region for various fare and operating cost assumptions. In addition, the total number and size of the aircraft making up the optimum mix are shown.

In presenting the system profit results it is assumed that two separate airline organizations are operating in each geographical region, that their routes are identical, and that the total traffic flow is divided equally between them.

In general, a review of these summaries shows that except for a few concepts the economic suitability of any concept relative to the others, if measured as the total profit to the operator, is difficult to establish with any degree of credibility in the meaning of the resulting order of preference (see figs. 44 through 46). (The numbers below the graphs indicate quantities of aircraft and passenger capacities; thus 26-90 means 26 aircraft, each with a 90-passenger capacity.)

Specifically, in each region, by reason of the different distribution of traffic demand versus city-pair distance, trends are evident that suggest the possible desirability, from an economic aspect, of certain concepts. For example, in the Northeast the rotor concepts (excluding the helicopter) appear most attractive, the demand density being heaviest in the 200-mile ranges; whereas on the West Coast, where the heaviest density is at approximately 350 miles, the jet lift and high-lift STOL designs appear to have a slight edge by the virtue of their marginally better profitability at longer ranges for the larger vehicles.

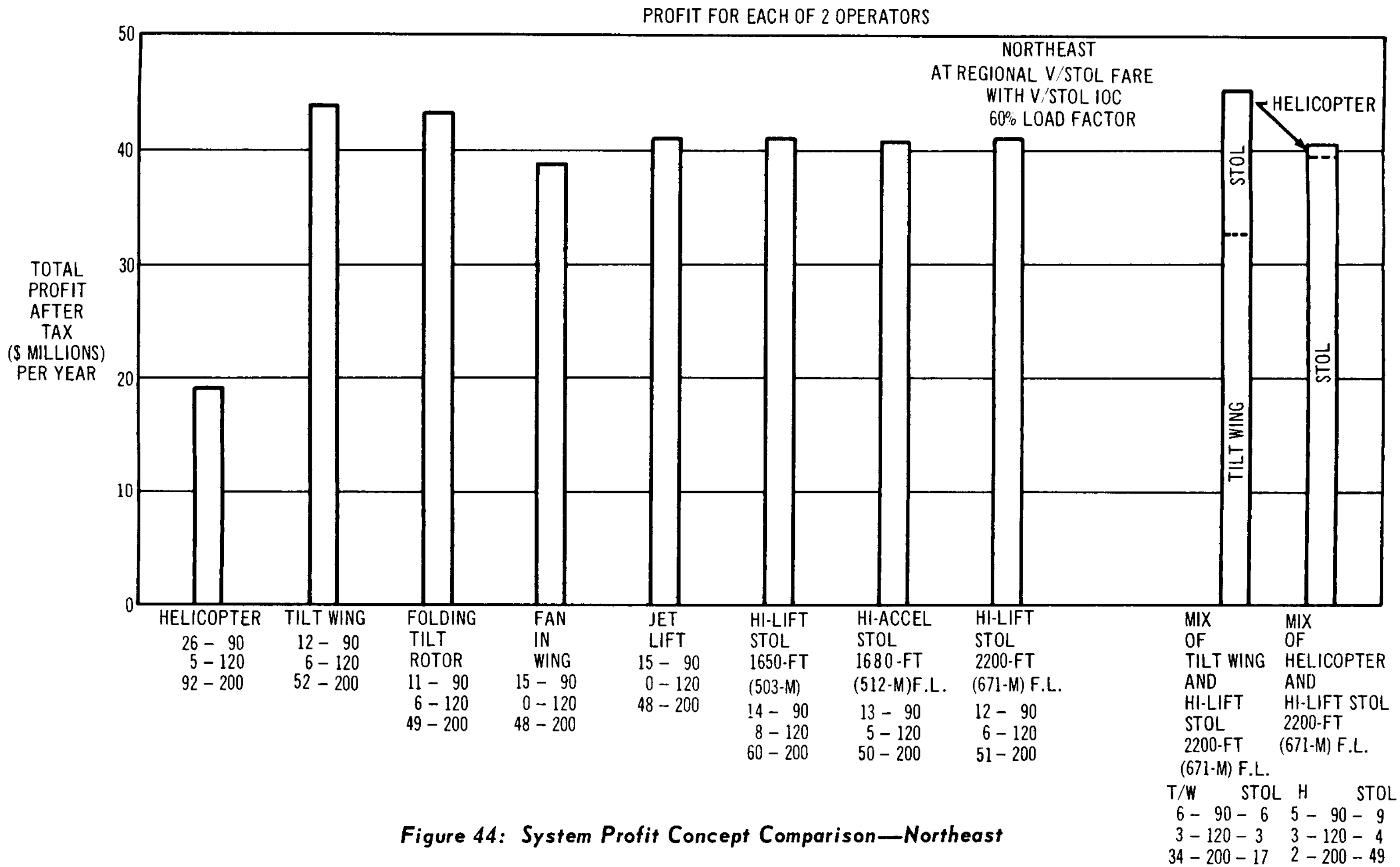


Figure 44: System Profit Concept Comparison—Northeast

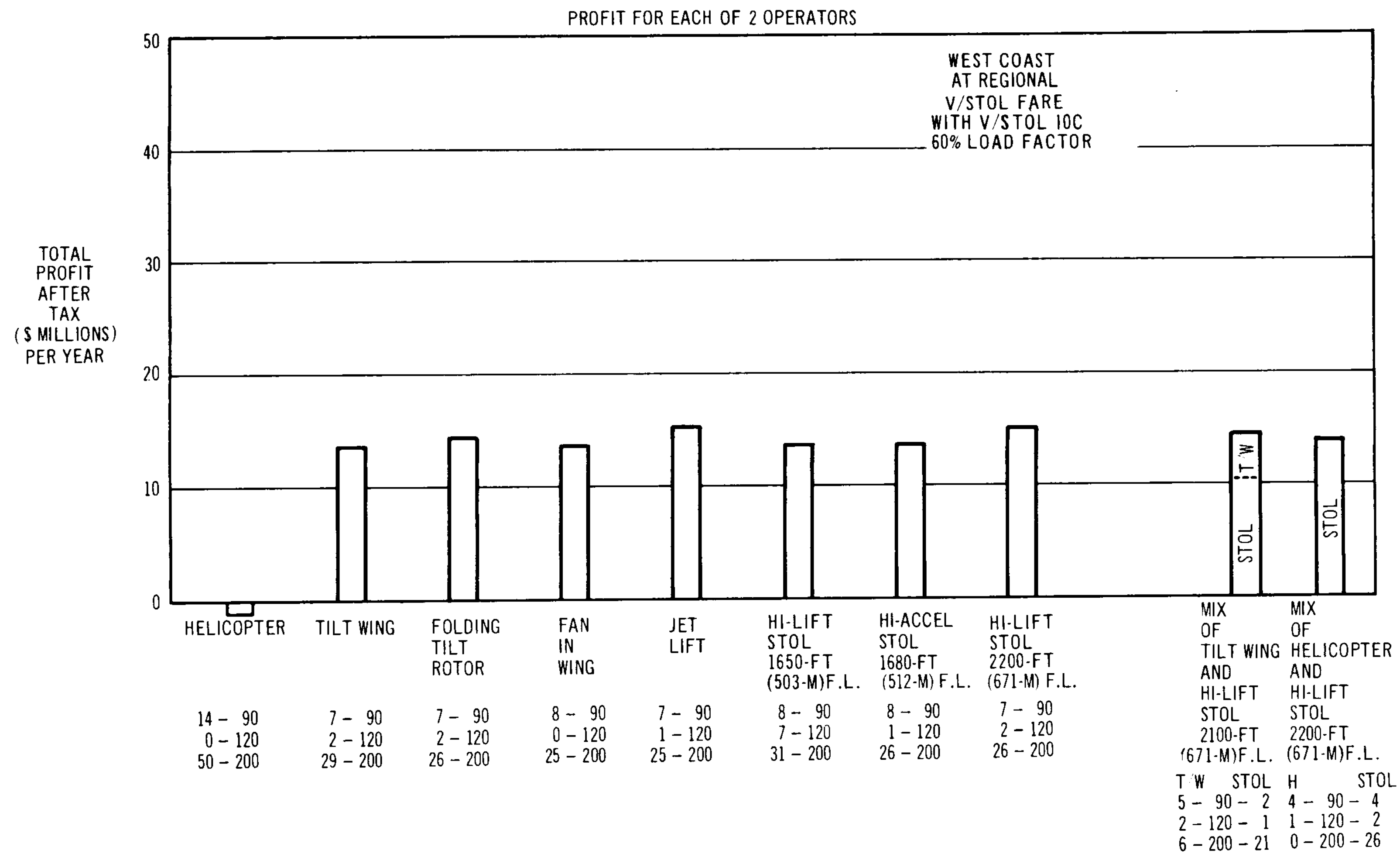


Figure 45: System Profit Concept Comparison—West Coast

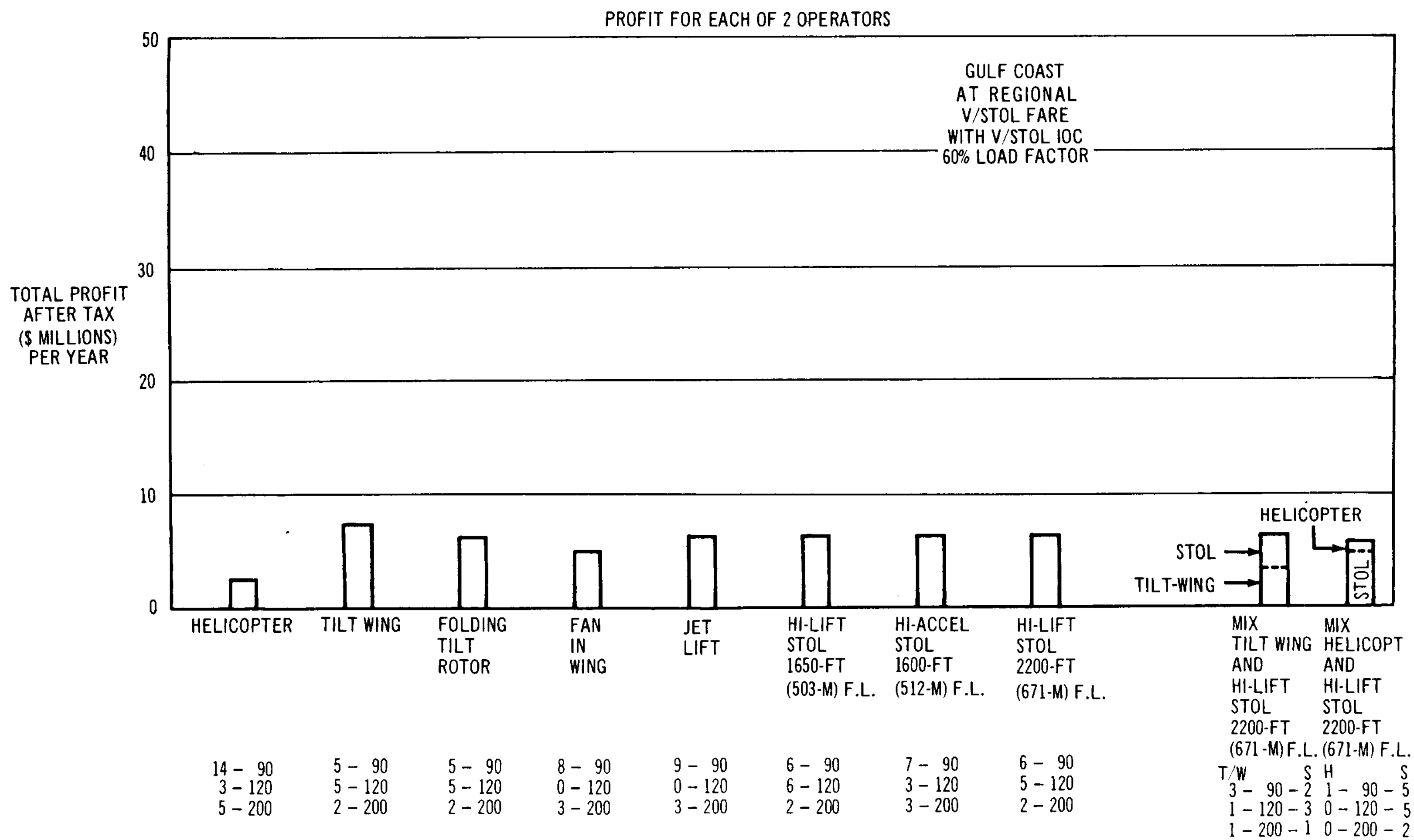


Figure 46: System Profit Concept Comparison—Gulf Coast

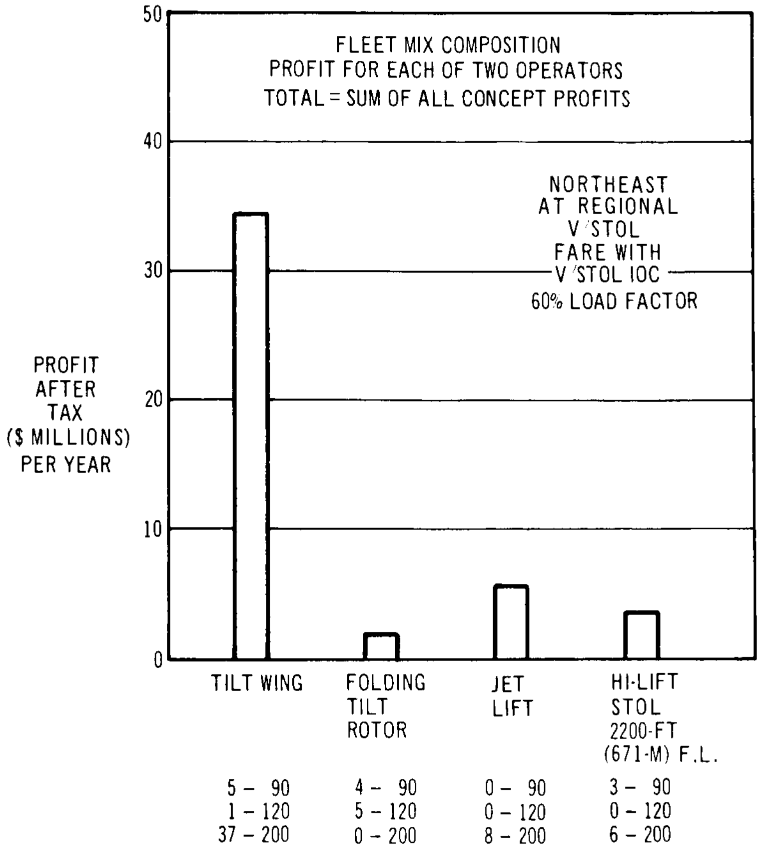


Figure 47: System Profit Optimum Fleet Mix—Northeast

Below each concept heading is shown the numbers of each size aircraft required in the fleet mix that optimizes the profit to the operator. In the case of the optimum fleet mix of concepts as well as aircraft sizes, figs. 47 through 49 show in each region what theoretically is the best mix to achieve the maximum profit. From fig. 50 it can be seen that in general the total profit returned by this optimum fleet mix of concepts can be very closely matched by either a single fleet of all tilt wing concepts, or all folding tilt rotors. Also in this figure can be seen the profitability of two postulated fleet mixes that could represent a developed first-generation V/STOL airline system. Specifically, one mix involves the use of only tilt wing aircraft at ranges below 230 mi with only the high lift STOL 2200-ft concept used at all ranges above. The second mix involves only helicopters below 150 mi with only the same STOL concept above 150 miles.

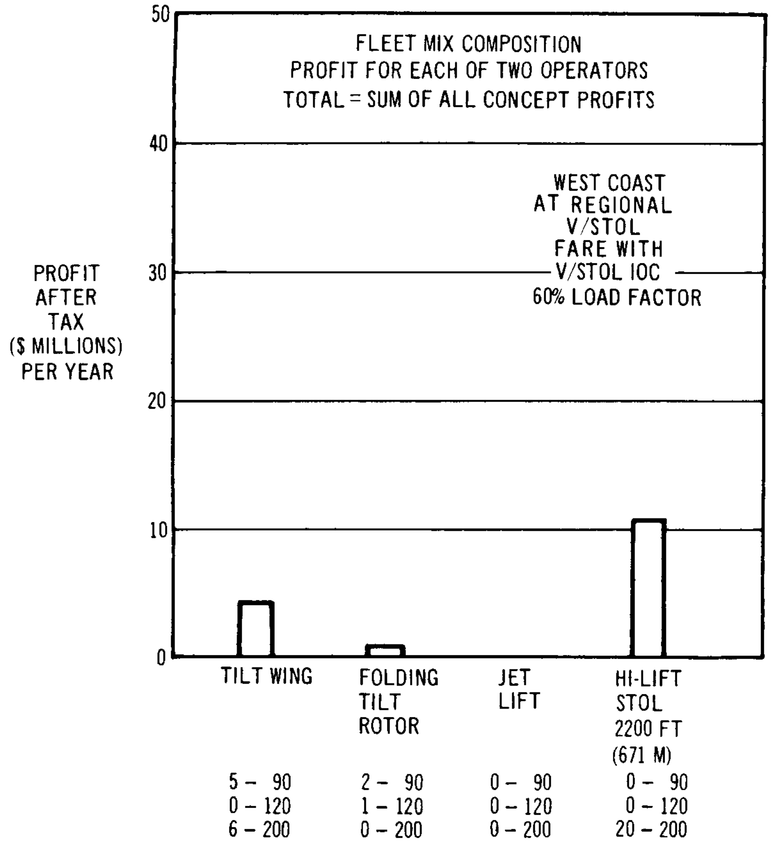


Figure 48: System Profit Optimum Fleet Mix—West Coast

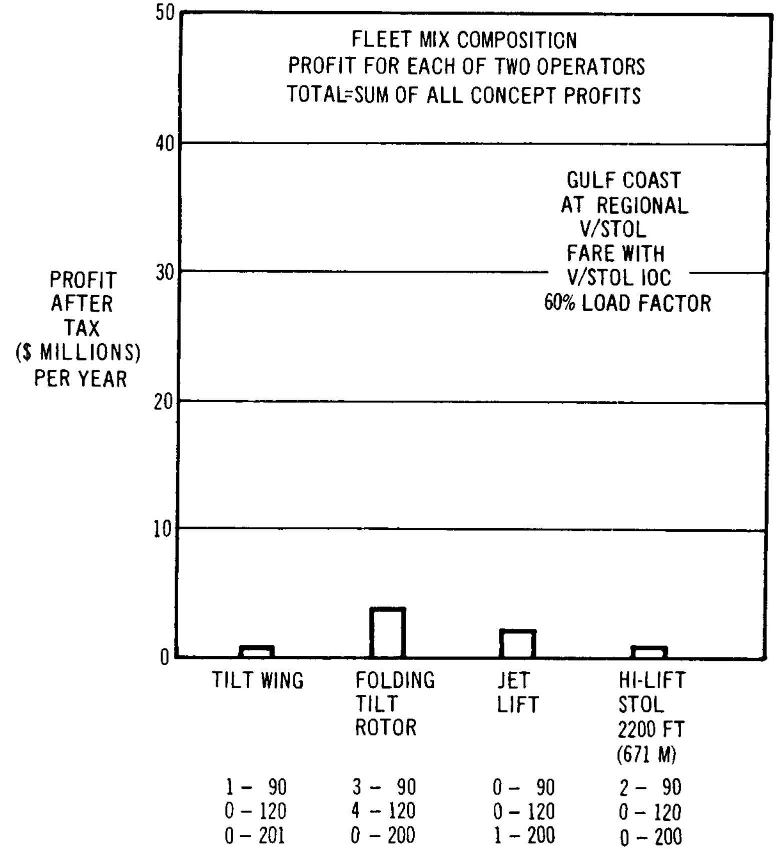


Figure 49: System Profit Optimum Fleet Mix—Gulf Coast

Figures 51, 52 and 53 show the effect on profit of reducing the indirect operating costs when the V/STOL ground facilities depreciation charge is set at the same level as a CTOL facility. While the profit is understandably higher, the correct treatment in this study of this factor is not critical to the objectives of NASA. It should be noticed that the STOL concepts benefit more from this change due to the larger increment of cost that is eliminated.

Of much greater significance is the effect on system profit, and hence the possible economic viability of a V/STOL system, of reducing the fare to the CTOL level, i.e., eliminating any premium in the fare for the V/STOL system relative to the CTOL system. This is shown in figs. 54 and 55 on a regional basis.

Again, this effect does not provide any better segregation means for arranging the relative economic suitability, with the exception of the helicopter. Alternatively, if it is possible to increase the fare to that level which will optimize the profit in each category, it can be shown that segregation of concepts can be improved.

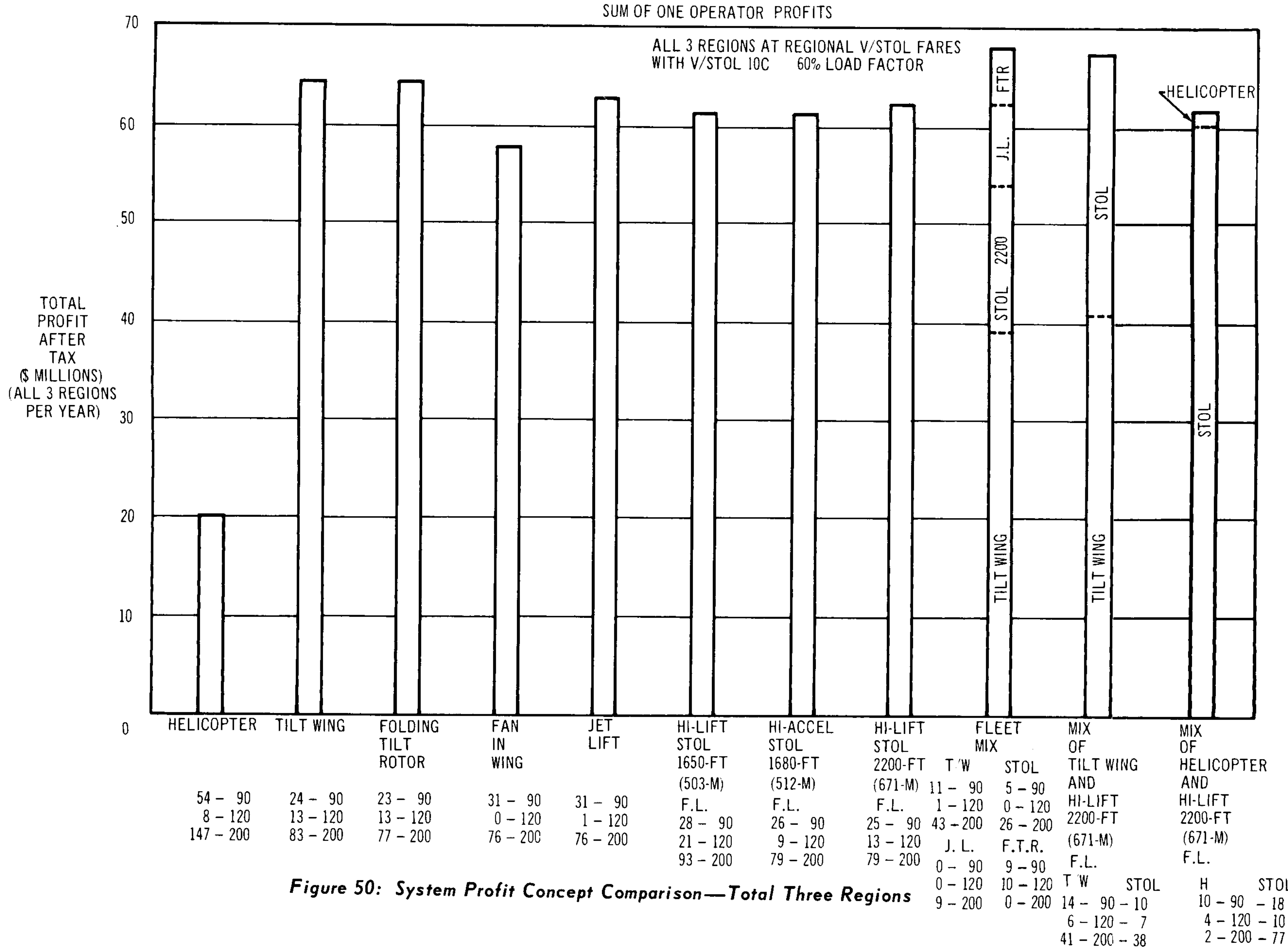


Figure 50: System Profit Concept Comparison—Total Three Regions

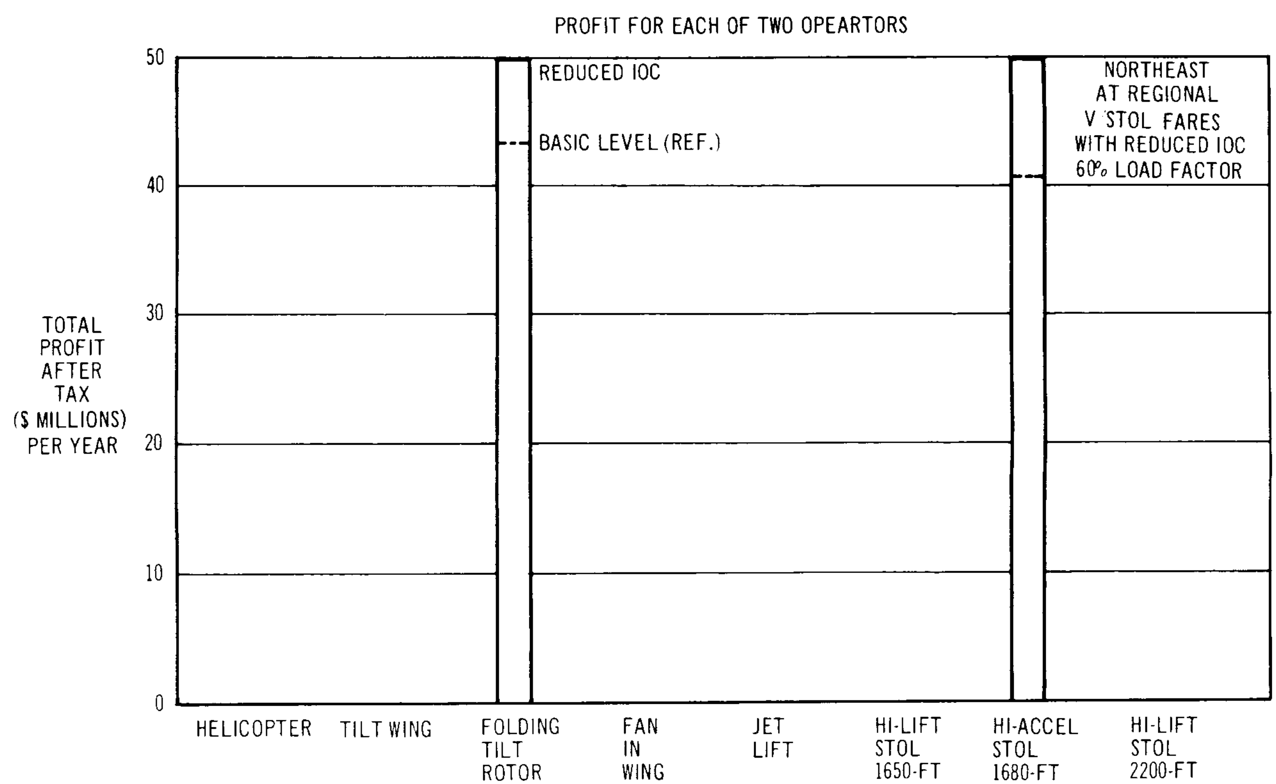


Figure 51: System Profit Effect of Reduced Facilities Depreciation—Northeast

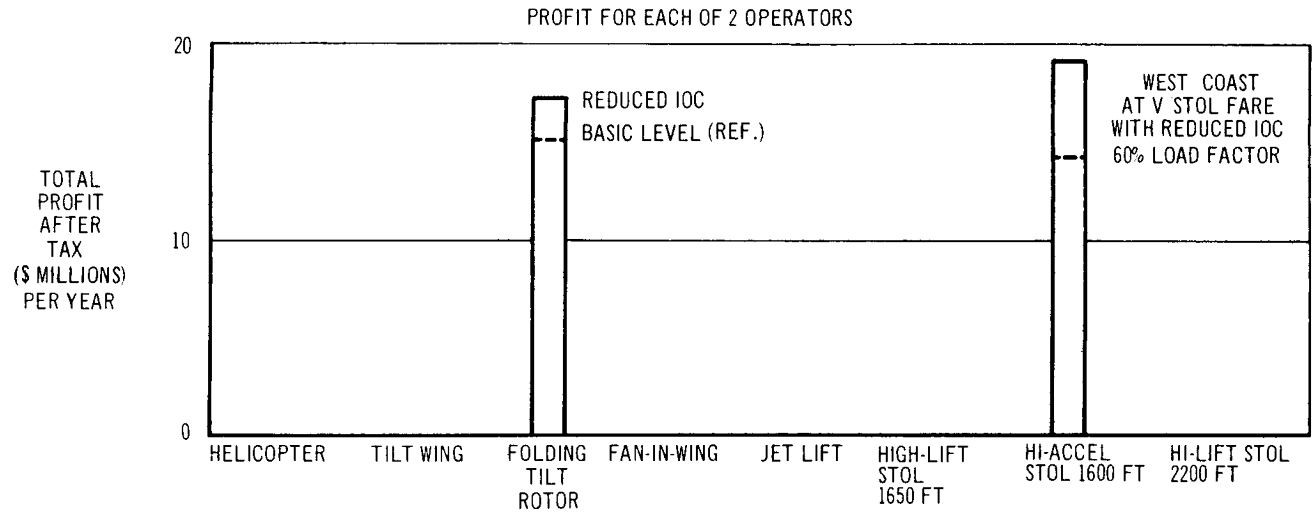


Figure 52: System Profit Effect of Reduced Facilities Depreciation—West Coast

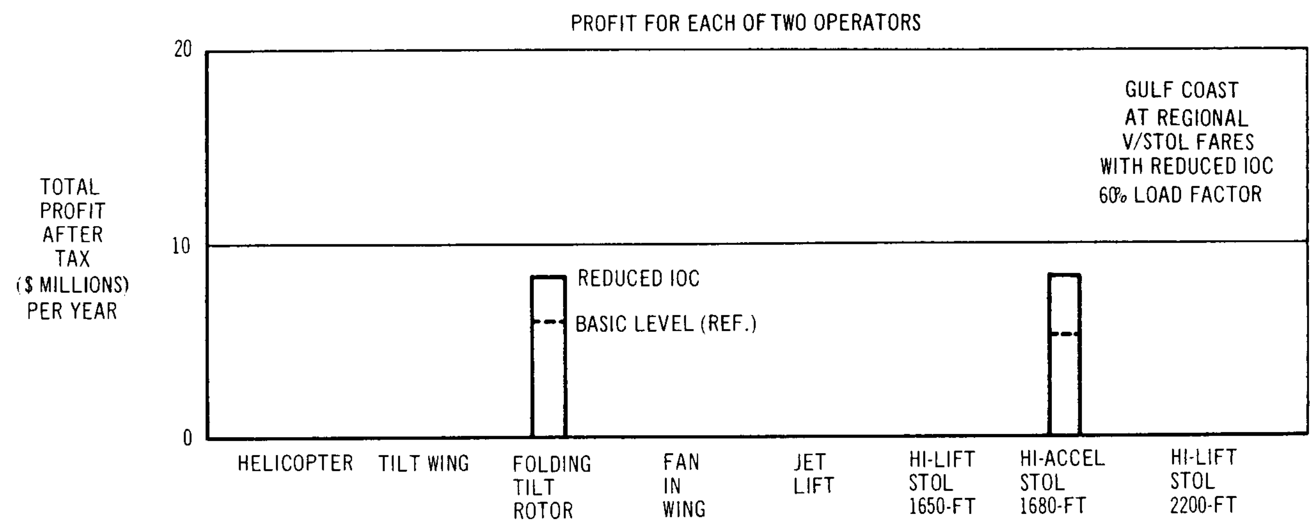


Figure 53: System Profit Effect of Reduced Facilities Depreciation—Gulf Coast

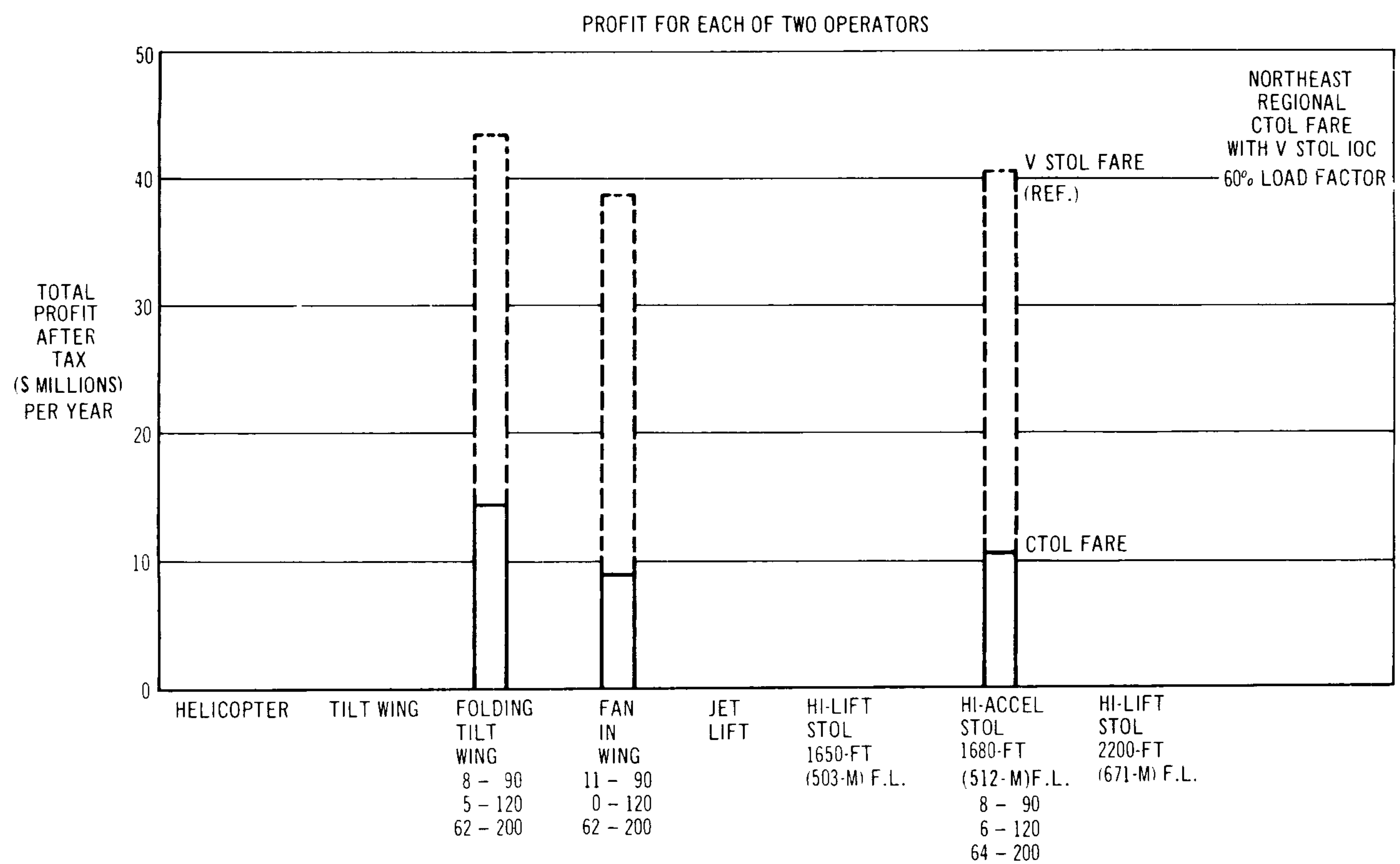


Figure 54: System Profit Effect of Reduced Fare Level—Northeast

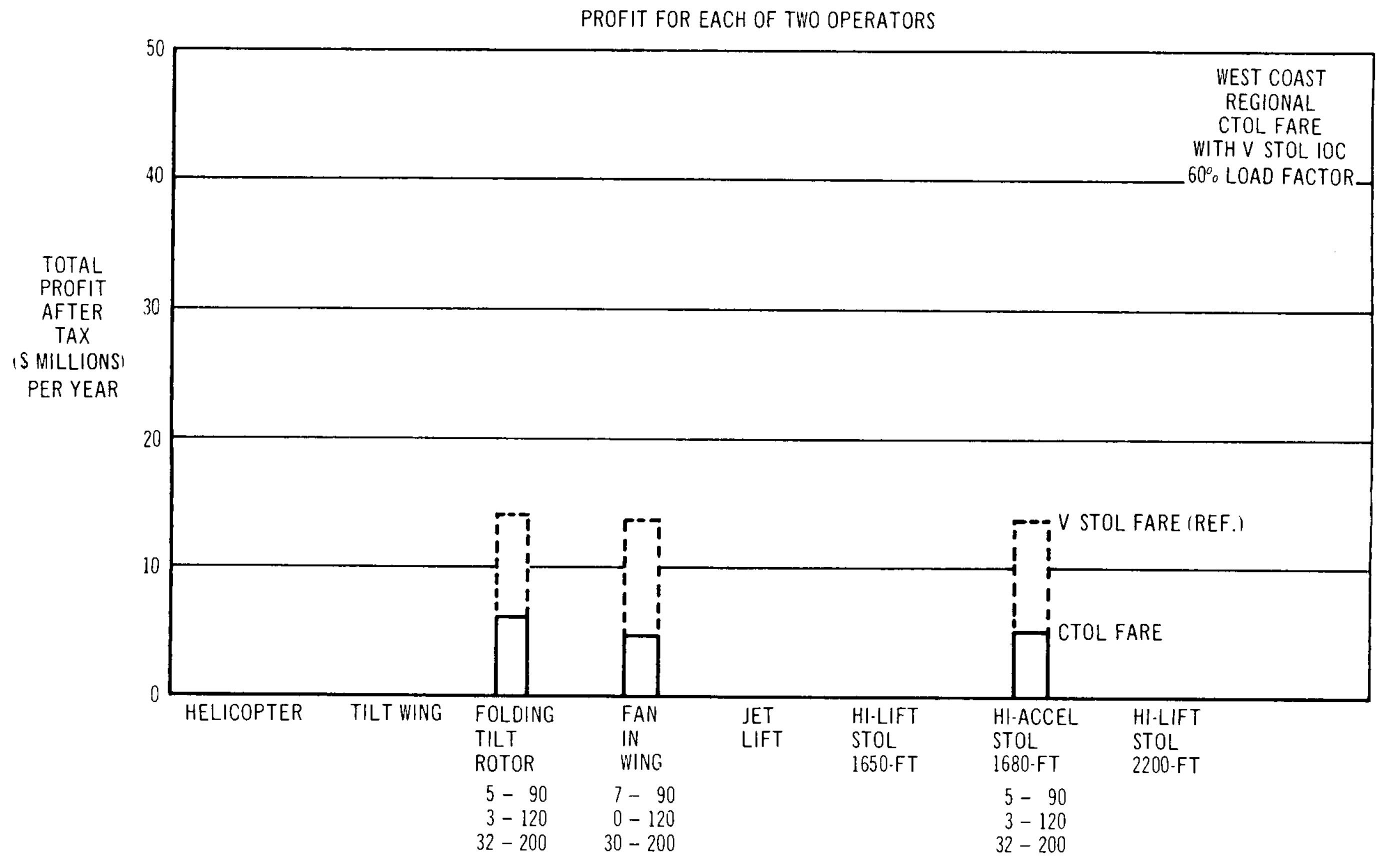


Figure 55: System Profit Effect of Reduced Fare Level—West Coast

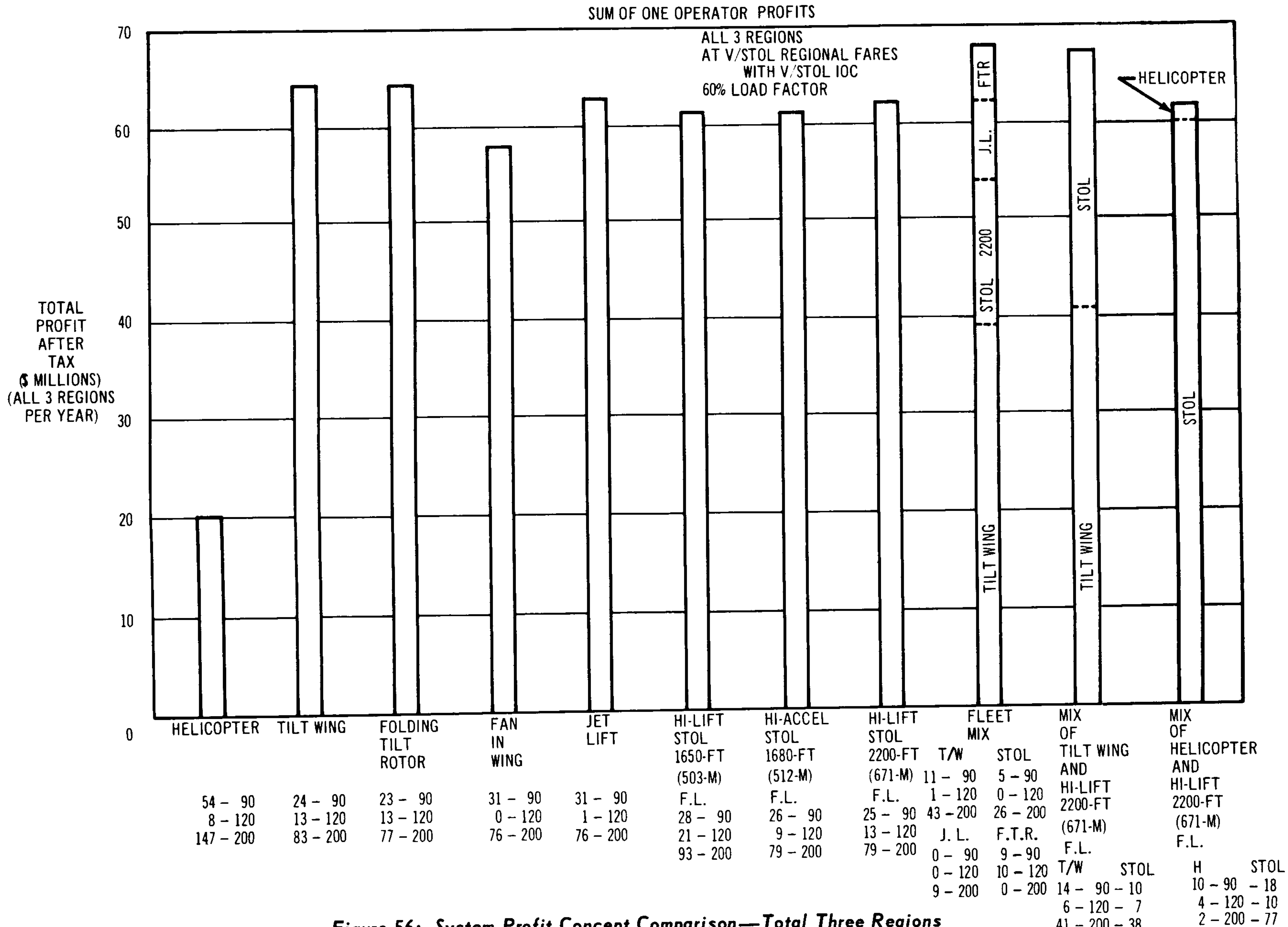


Figure 56: System Profit Concept Comparison—Total Three Regions

Next is presented a series of summary charts showing the effect that some of the design and operational sensitivity factors have on system profit. Figure 57 shows how more critical is hover time to the nonrotor concepts, and again how little hover time can be allowed on a continuous yearly basis before the profit capability of the VTOL concepts suffers relative to the STOL concepts. A discussion of hover time as it may be affected by the assumptions of weather conditions and electronic landing aid capability can be found elsewhere in this report. It generally concludes that 1% to 2% of yearly operations may be subject to a hover time penalty of possible 30 sec.

On the other hand, fig.58 shows that all concepts suffer similarly due to additional air maneuver times. A low profit producer such as the helicopter can be severely affected by this operational penalty.

Similarly, fig. 59 shows the effect of additional ground maneuver time. All three figures relating to hover and maneuver times are prepared on the assumption that every trip made during the year suffers these penalties. The effect on profit of a variation in total operating costs is shown in fig. 61 A change of approximately ± 10% in TOC could represent a change of ± 20% in either DOC or IOC.

To provide some measure of the contribution of the various technology advances, the profit comparison of fig. 62 is presented. It shows the profit levels that each concept can attain operating in a 1985 environment with a 1985 size market and traffic demand but with all the concepts first designed with the current technology in all disciplines. Next is shown, incrementally, how much more profit would be attained if the 1985 level of technology is used again in each discipline separately. Finally, the basic 1985 profit level is shown, in which all technology advances are used together. (In this case the weight increment is composed of the fixed equipment and the advanced filament composites, the advanced titanium material not being considered in the total plot.) It must be emphasized that the profit level using a 1966 technology must not be considered as a possible 1966 profit level, because the market size used is that for 1985, some ten times that of 1966. Further, 1966 technology should not be inferred as indicating that any concept could be built tomorrow, for there are concepts and power plant developments involved not currently available.

Essentially this chart concludes that technology advances in weight reduction are by far one of the most powerful in improving the economic possibilities of all concepts, but it should be recognized that this chart does not indicate the amount of development time and money involved in these advancements. Hence, it is possible that the advancements in aerodynamics and engine technology may be easier to attain than some of those in the advanced structural materials area. Included in each of these concept presentations are the advances assumed for the various lift and augmented power systems in three areas: (1) increased usable life, (2) increased reliability, and (3) increased times between overhaul, all of which also appreciably enhance the economic possibility of some of the concepts.

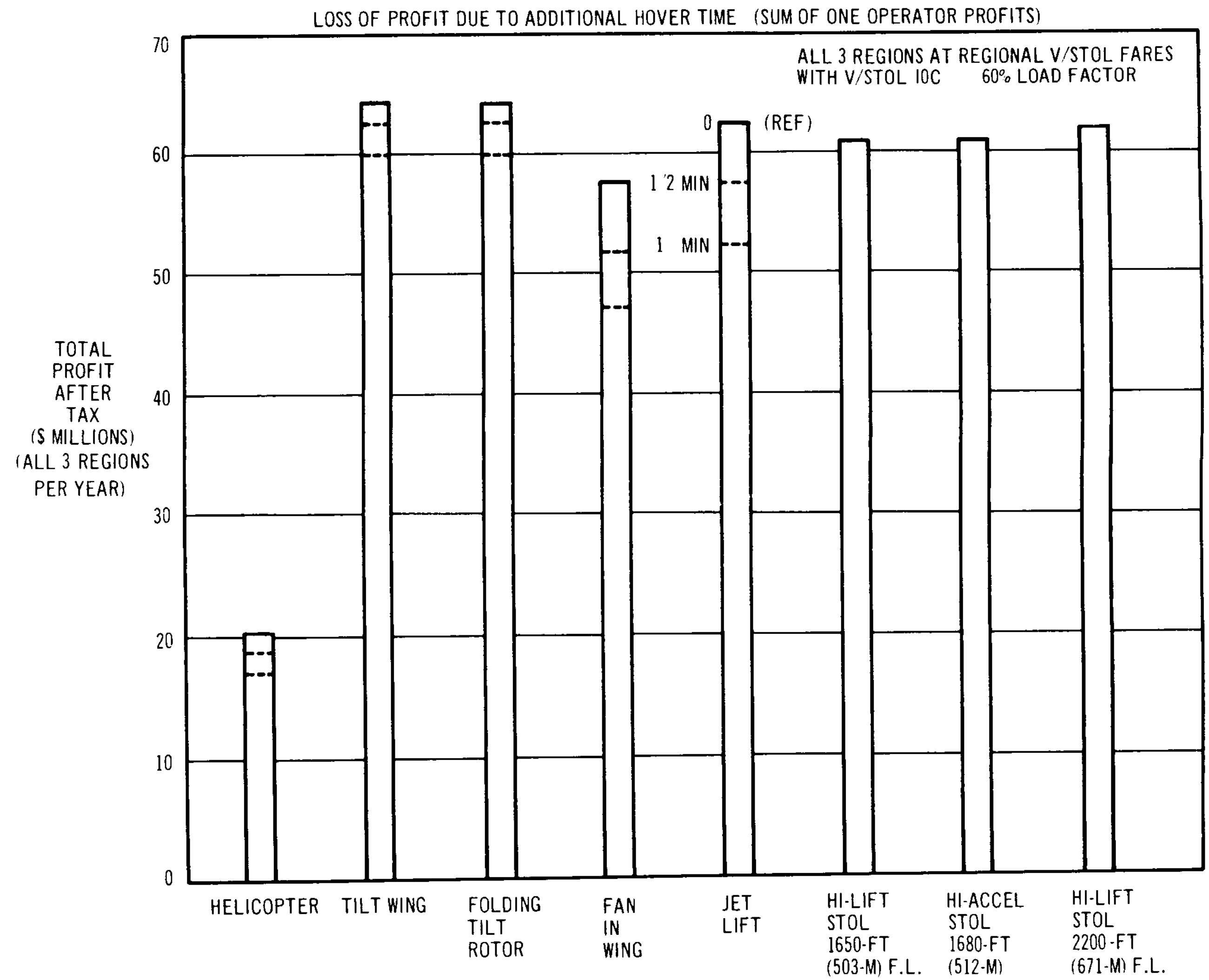


Figure 57: System Profit Effect of Hover Time—Total Three Regions

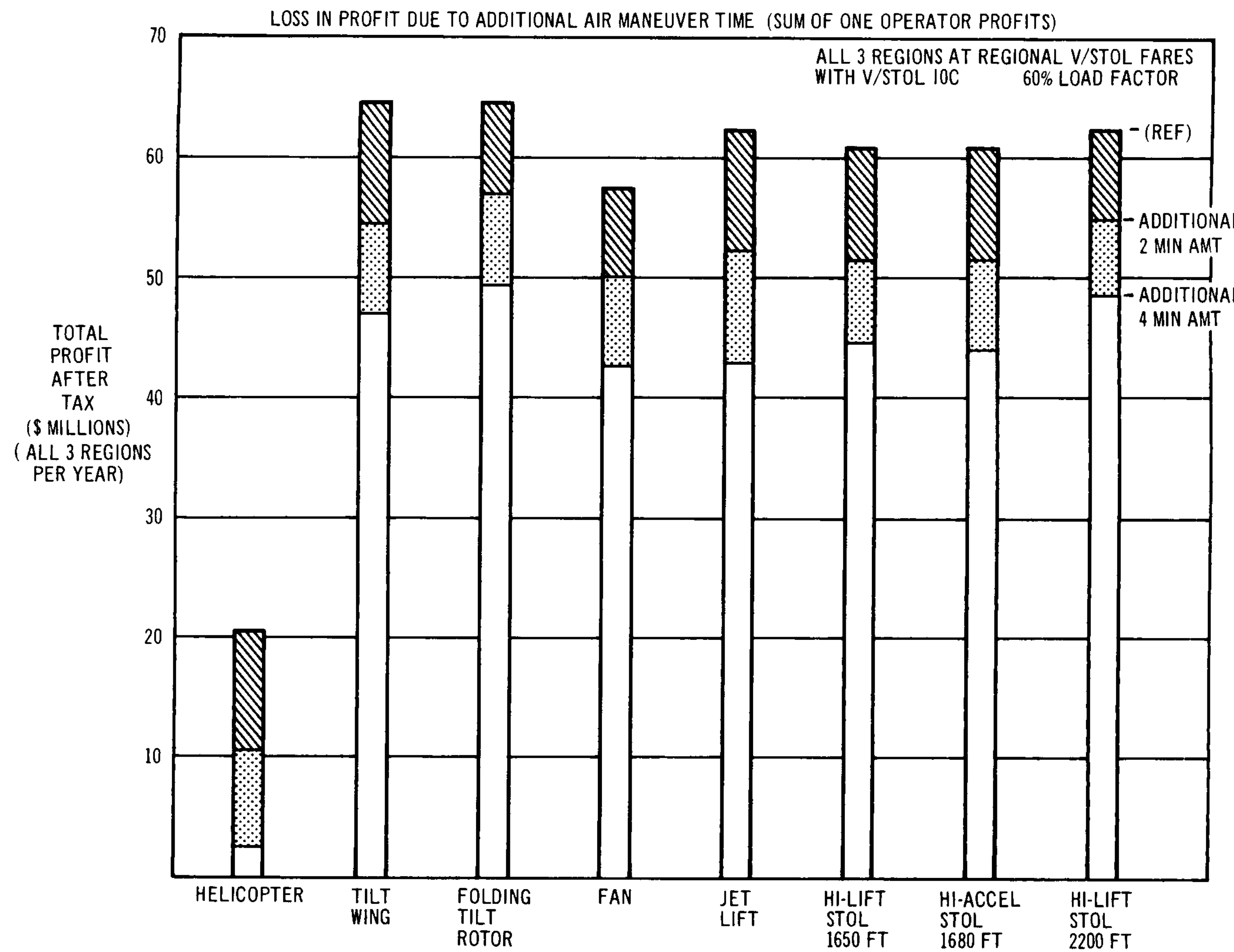


Figure 58: System Profit Effect of Additional Air Maneuver Time—Total Three Regions

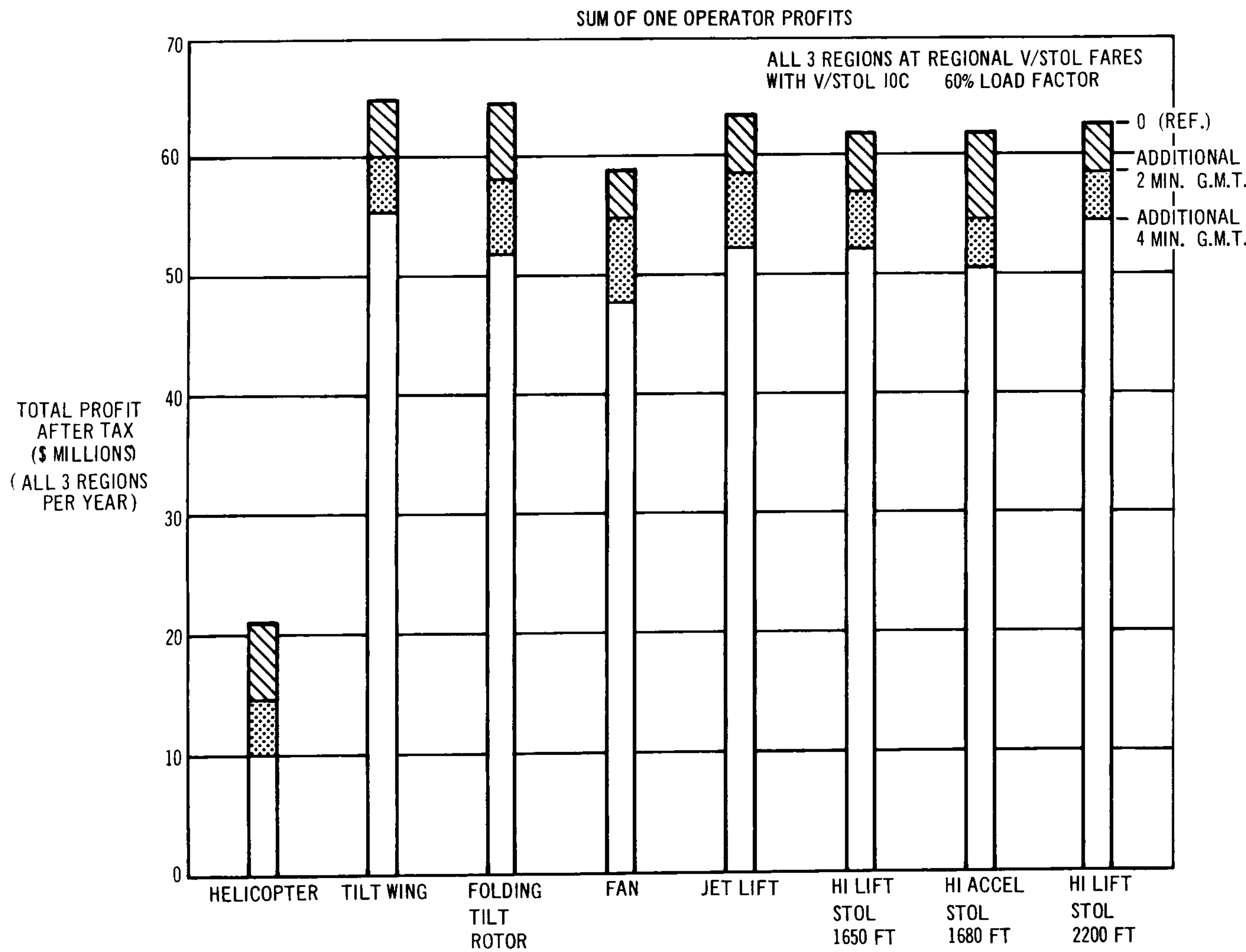


Figure 59: System Profit Effect of Additional Ground Maneuver Time—Total Three Regions

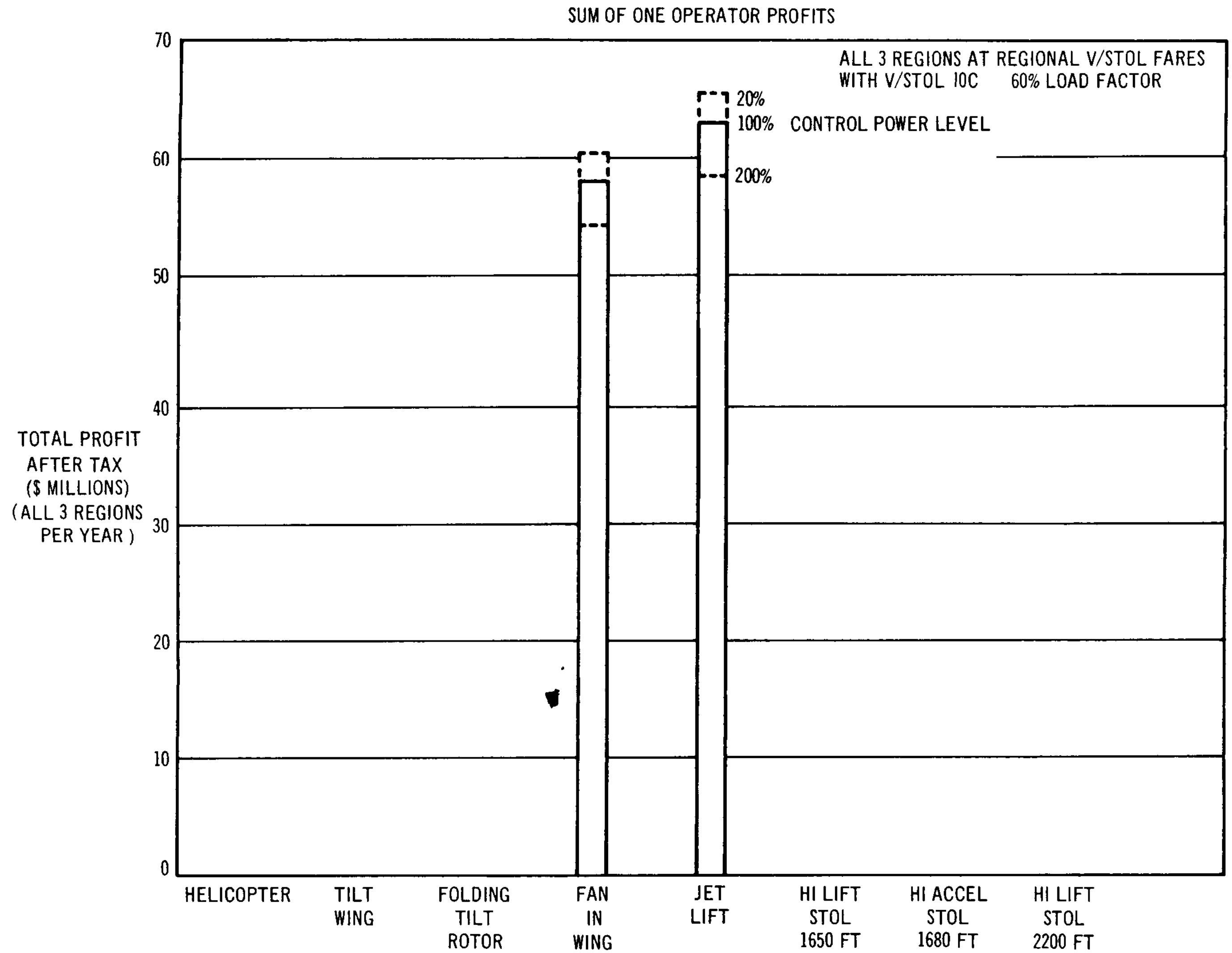


Figure 60: System Profit Effect of Design Control Power Level—Total Three Regions

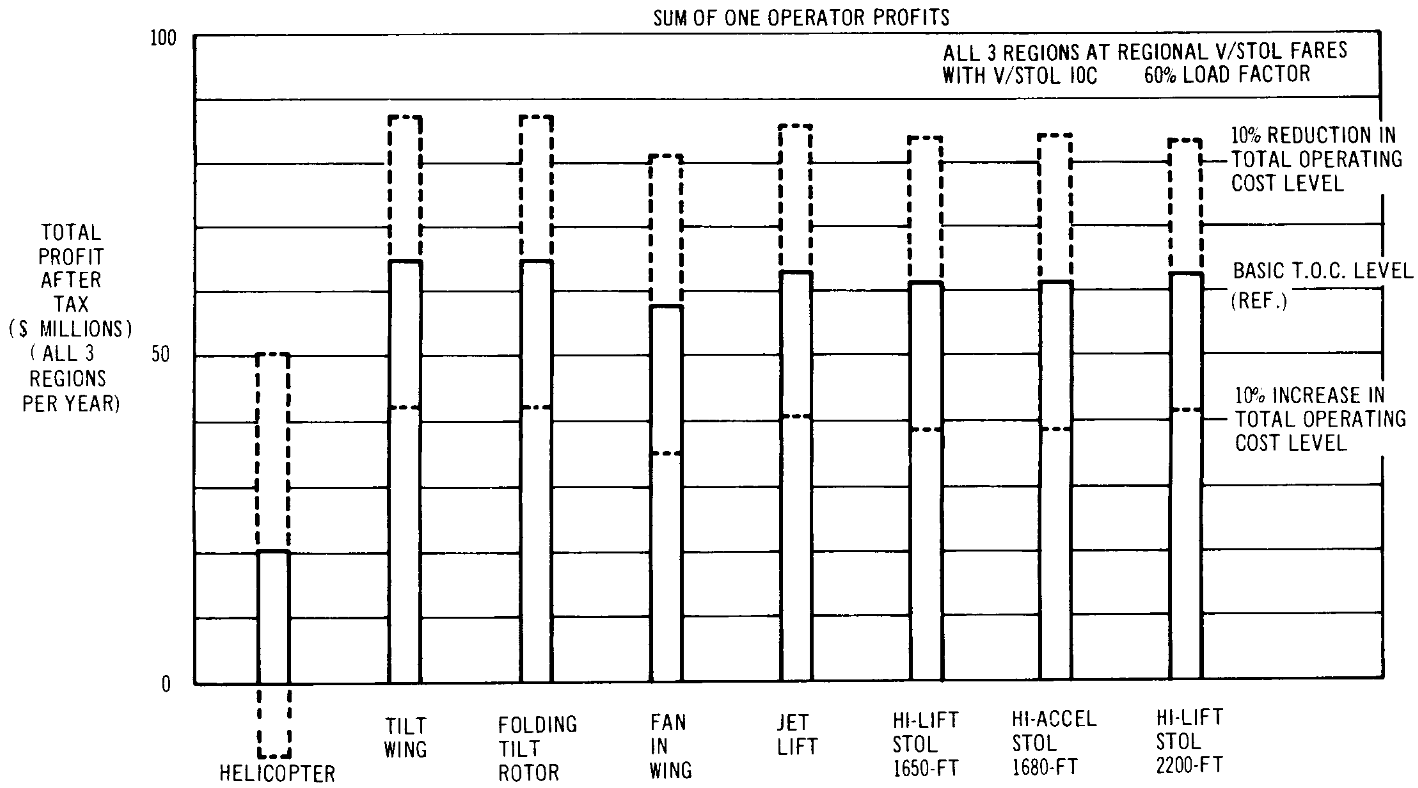


Figure 61: System Profit Effect of Variation in Total Operating Cost—Total Three Systems

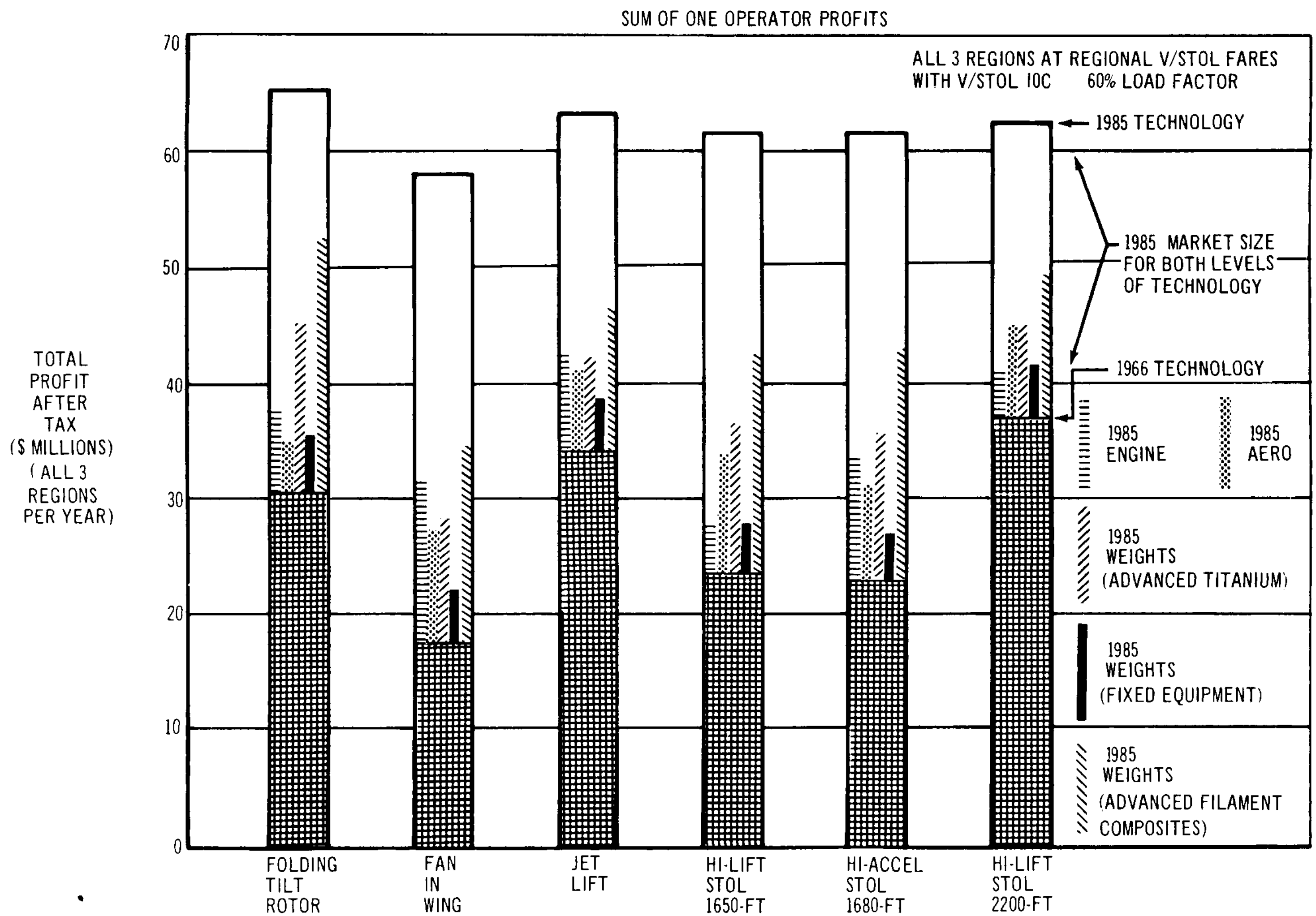


Figure 62: System Profit Effect of Technology Contributions—Total Three Systems

Previously, the system profit levels were shown for two definitions of V/STOL fare, one at the CTOL level and one at the indifference level (i.e., CTOL fare plus difference in terminal access costs). If it is assumed that a further premium above the CTOL fare might be possible if the traveler values the time he saves, then the operator can increase the fare level above the indifference value.

Referring to fig. 63 , it is possible to establish the optimal fare in each category for each concept, when the value of time is specified, in this case, as equal to the traveler's salary. (See the discussion in sec. 7.2.3.9 for the methodology involved here.) Hence it is apparent that if complete freedom in setting the fare were possible, better segregation could be established among the concepts. Even then this is only separating the STOL concepts from the VTOL.

Figure 64 shows this effect on a total systems basis, where the optimal fare has been used in each category. An analysis of the type shown in fig. 63 can provide visibility to the problem of what happens to category, and hence system, profit if the suburb STOL has access times and costs equal to the CTOL aircraft, rather than midway between VTOL and CTOL. It shows that whether the profits are calculated at an indifference fare level or at an optimal fare level (i.e., where the value of the traveler's time is recognized), the effect of different access time is not significant, but the fact is that access cost is higher and hence the V/STOL fare must be lower (by definition of indifference costs). This has a far greater effect on reducing the profitability of this STOL concept.

Finally, charts are presented for each concept that summarize most of the design and operational sensitivities that are analyzed as they affect the system profit (see figs. 65 through 72).

A further figure of merit of economic suitability is presented (see figs. 73 through 75) that is recognized as being a very much simplified "investment" measure, but it indicates again that concept segregation, while slightly more apparent, is still not made any more certain.

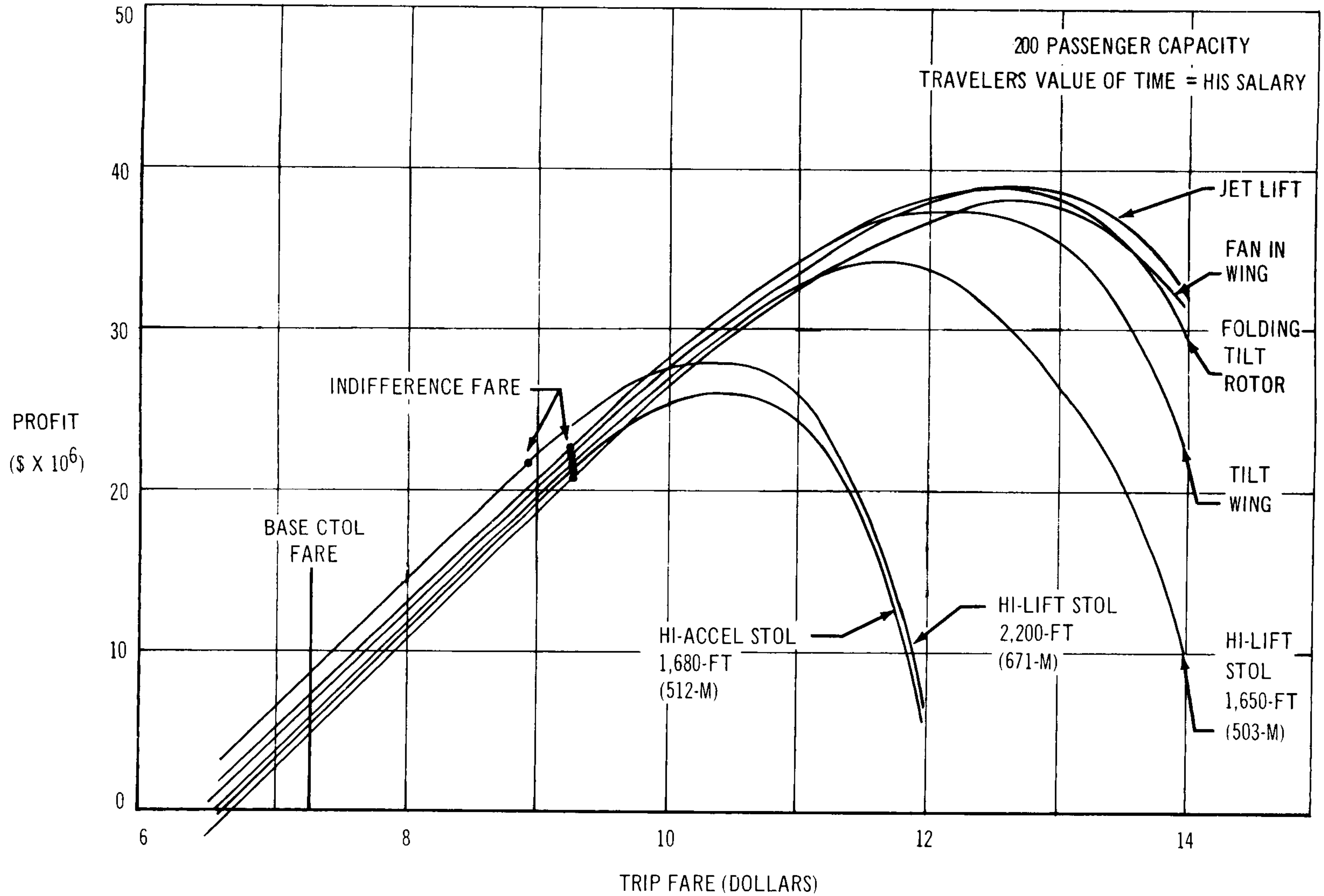


Figure 63: Optimal Fare Analysis—Northeast NYC-DCA

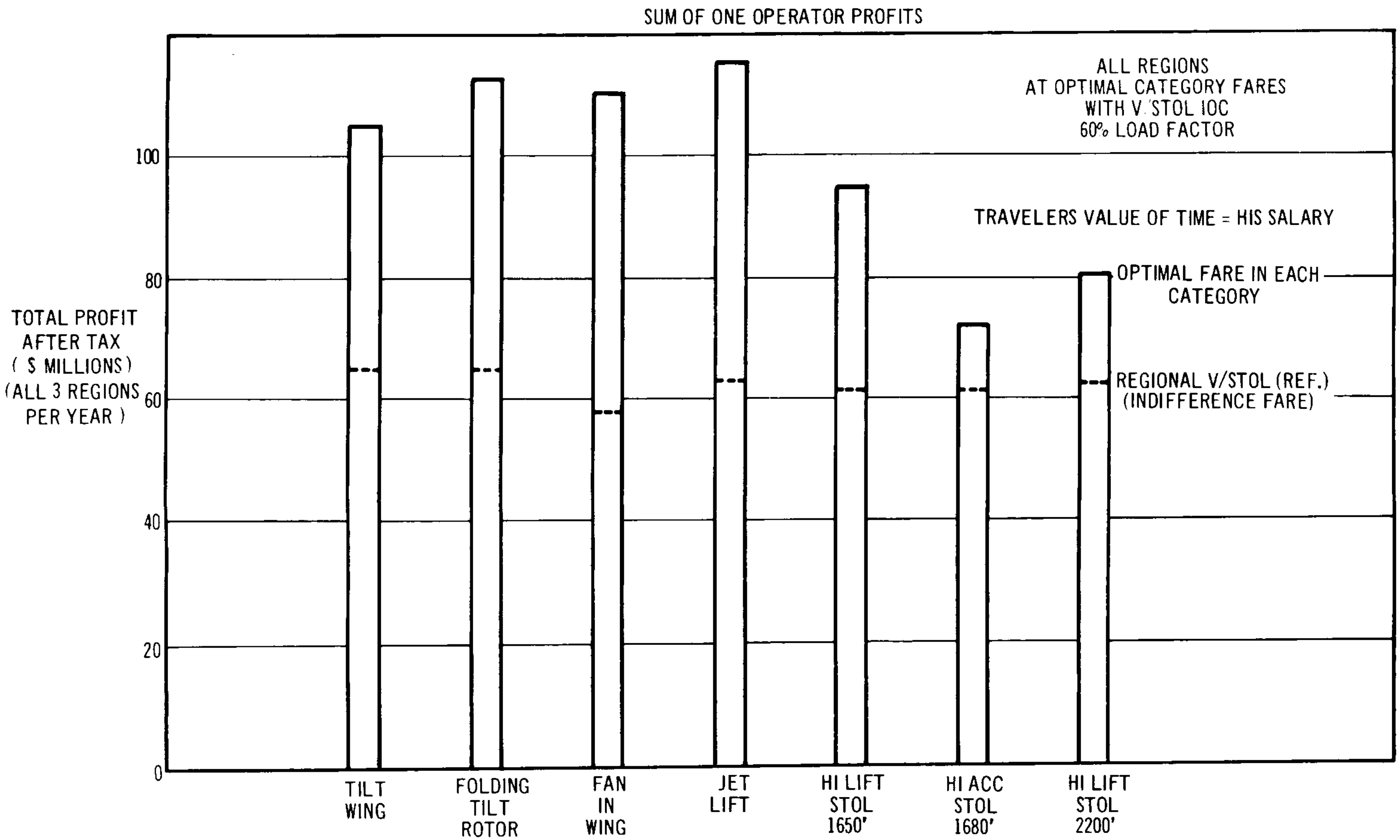


Figure 64: System Profit Effect of Optimal Fare—Total Three Regions

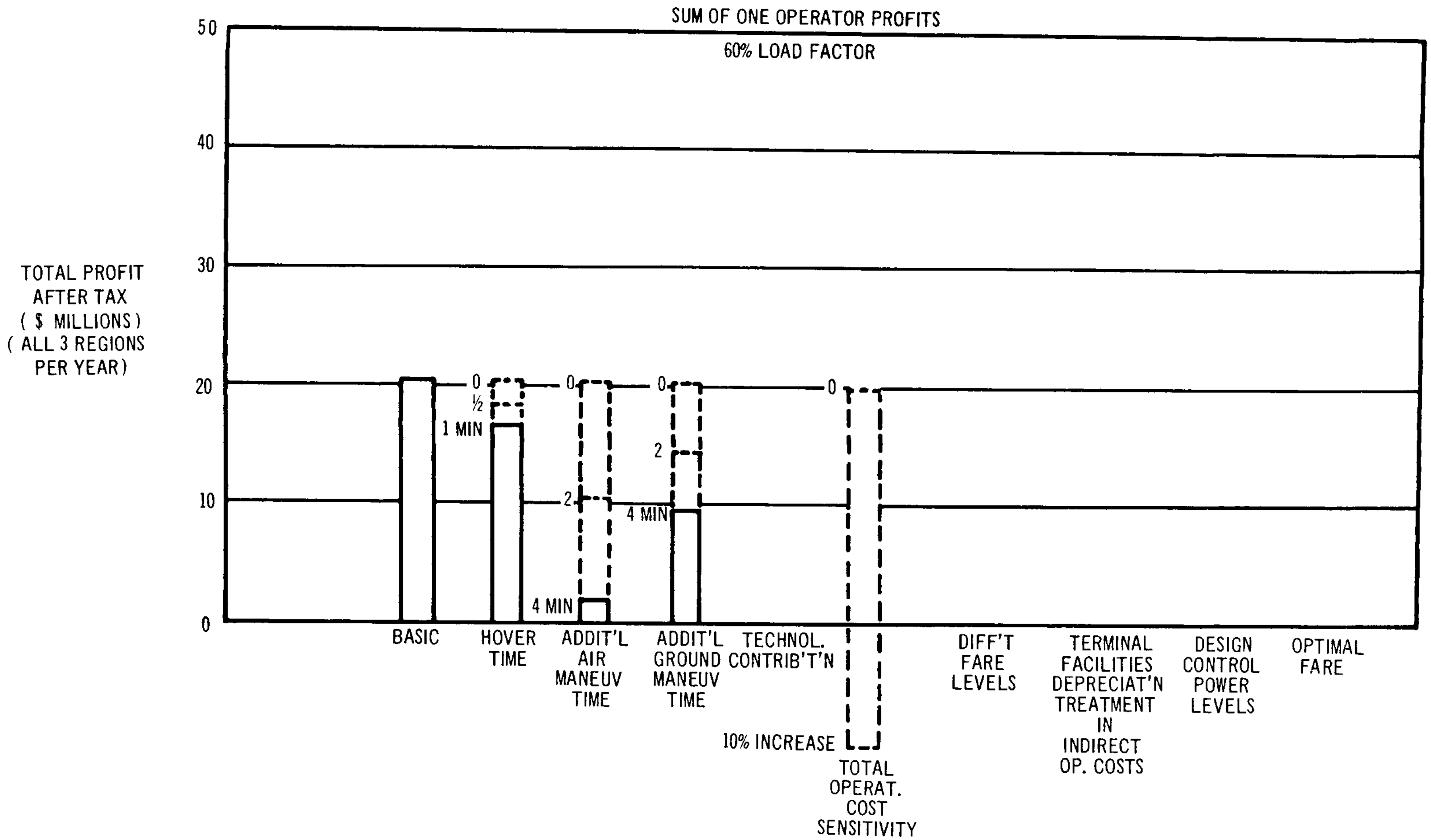


Figure 65: System Profit Concept Summary—Helicopter

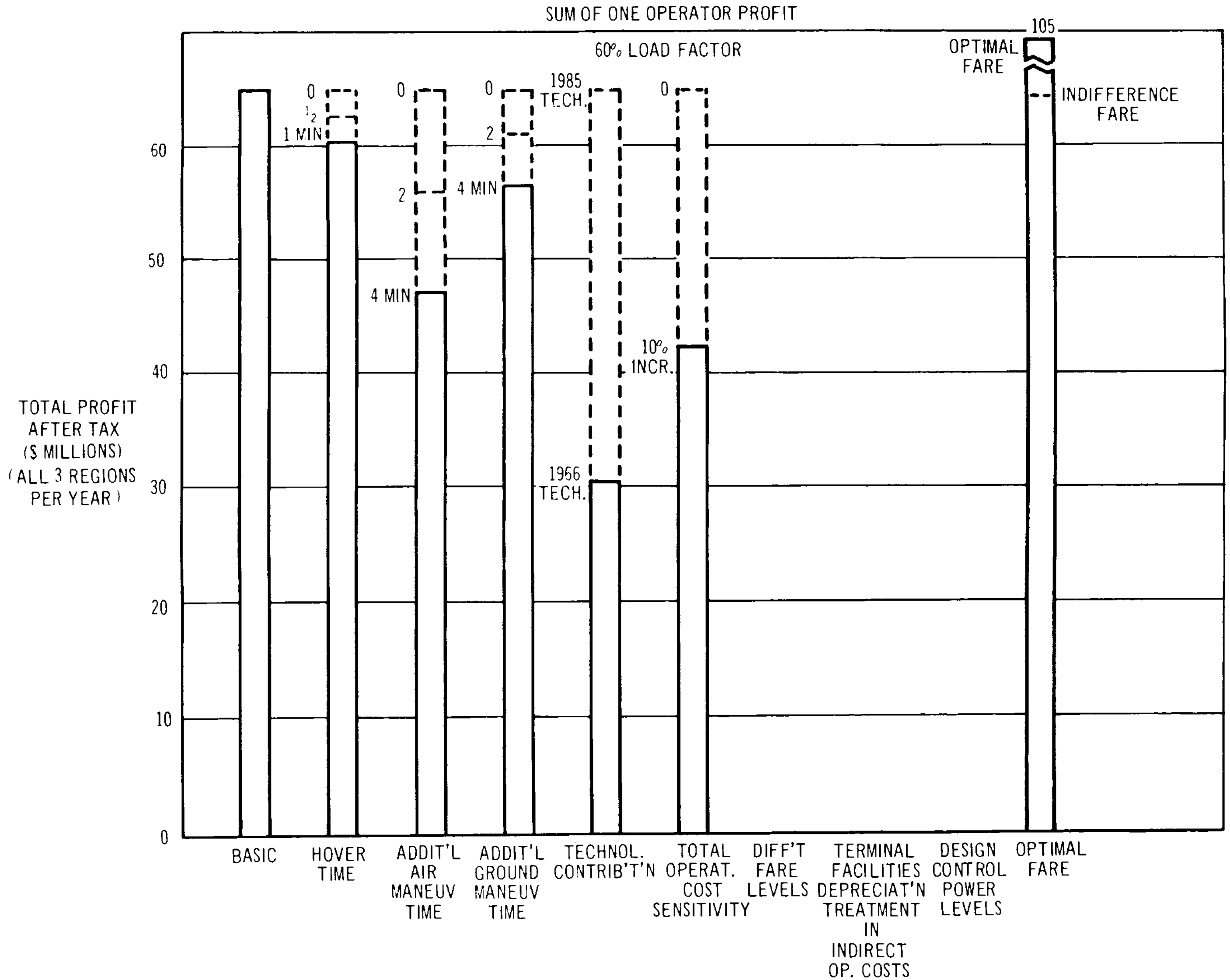


Figure 66: System Profit Concept Summary—Tilt Wing

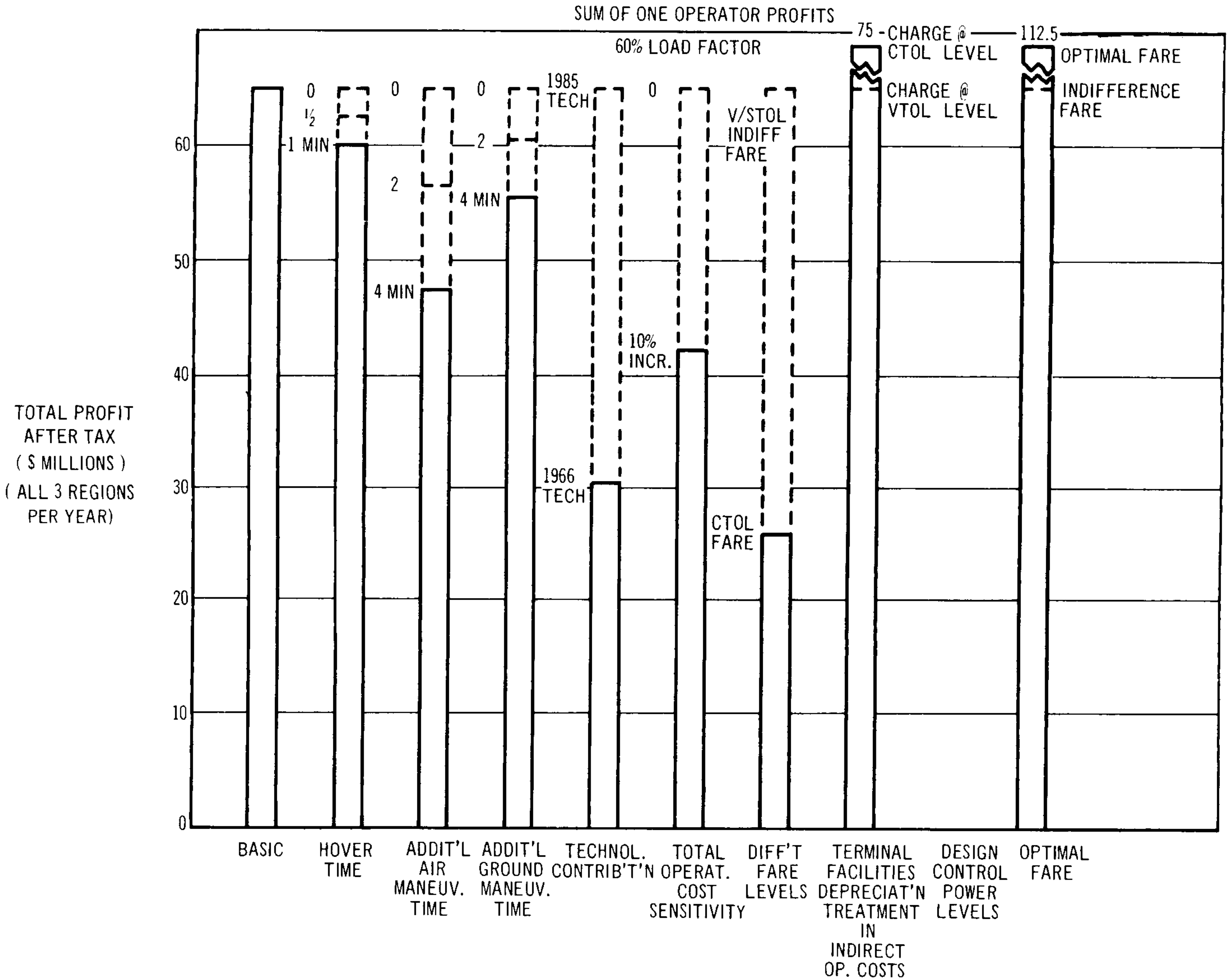


Figure 67: System Profit Concept Summary—Folding Tilt Rotor

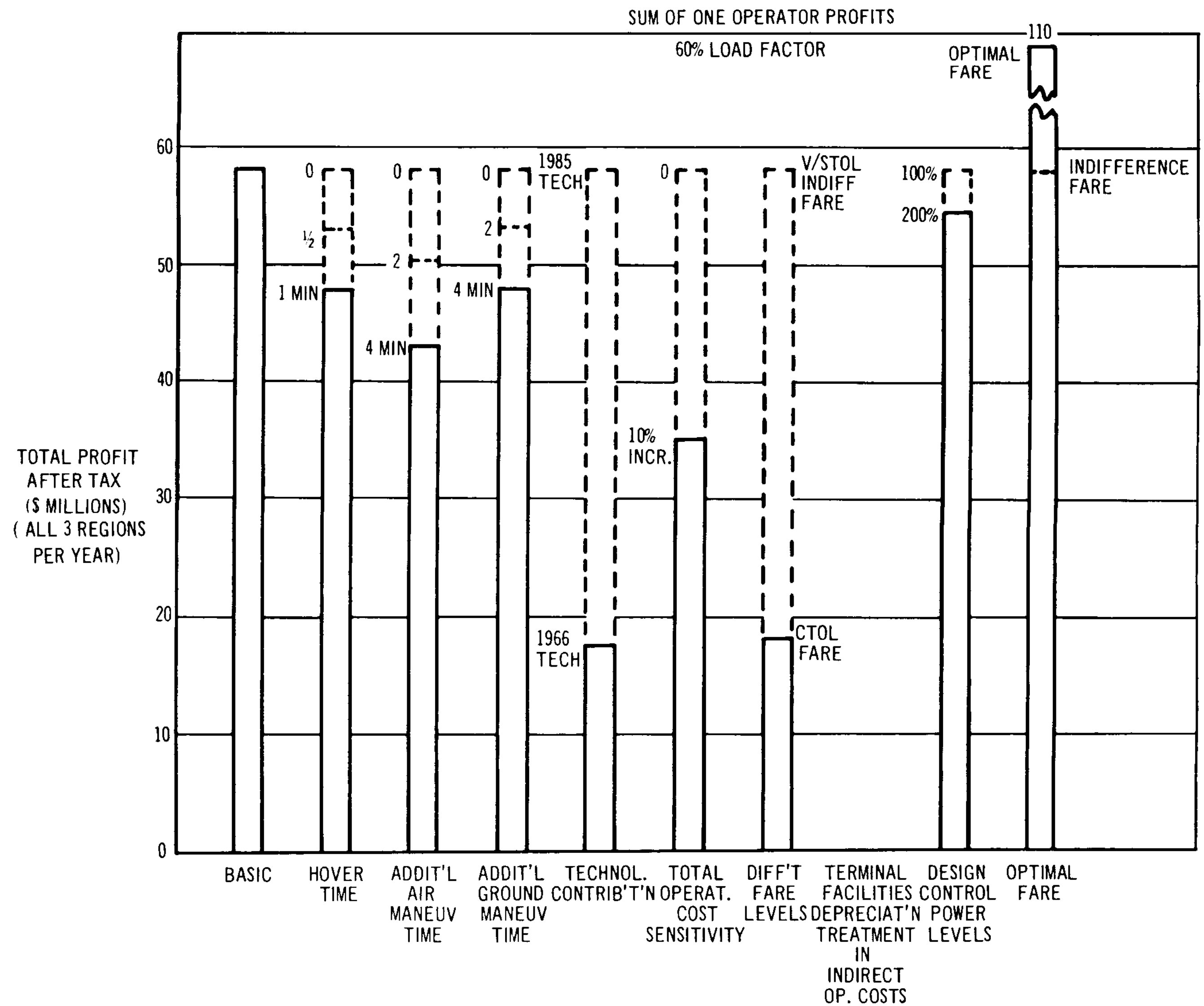


Figure 68: System Profit Concept Summary—Fan-in-Wing

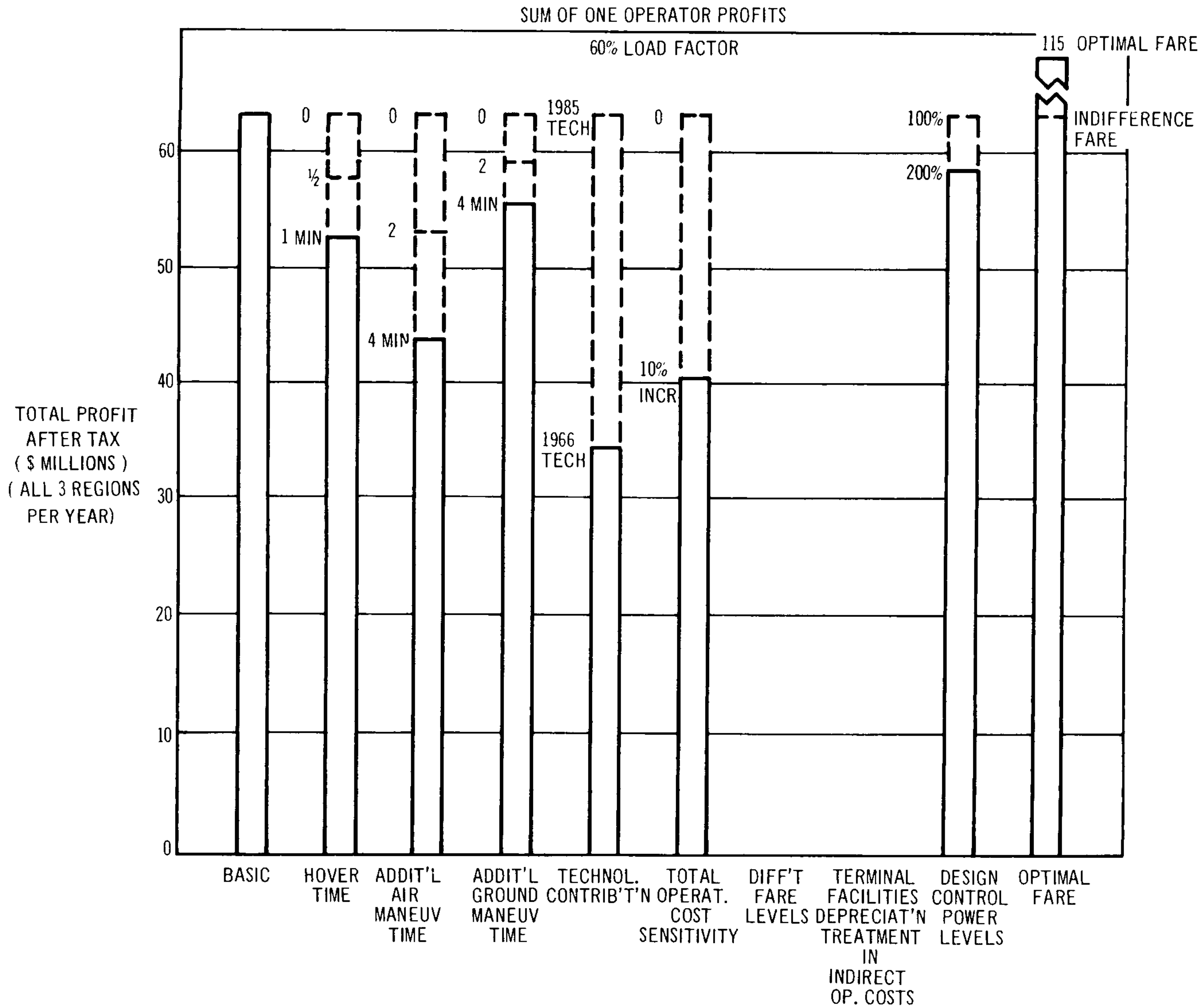


Figure 69: System Profit Concept Summary—Jet Lift

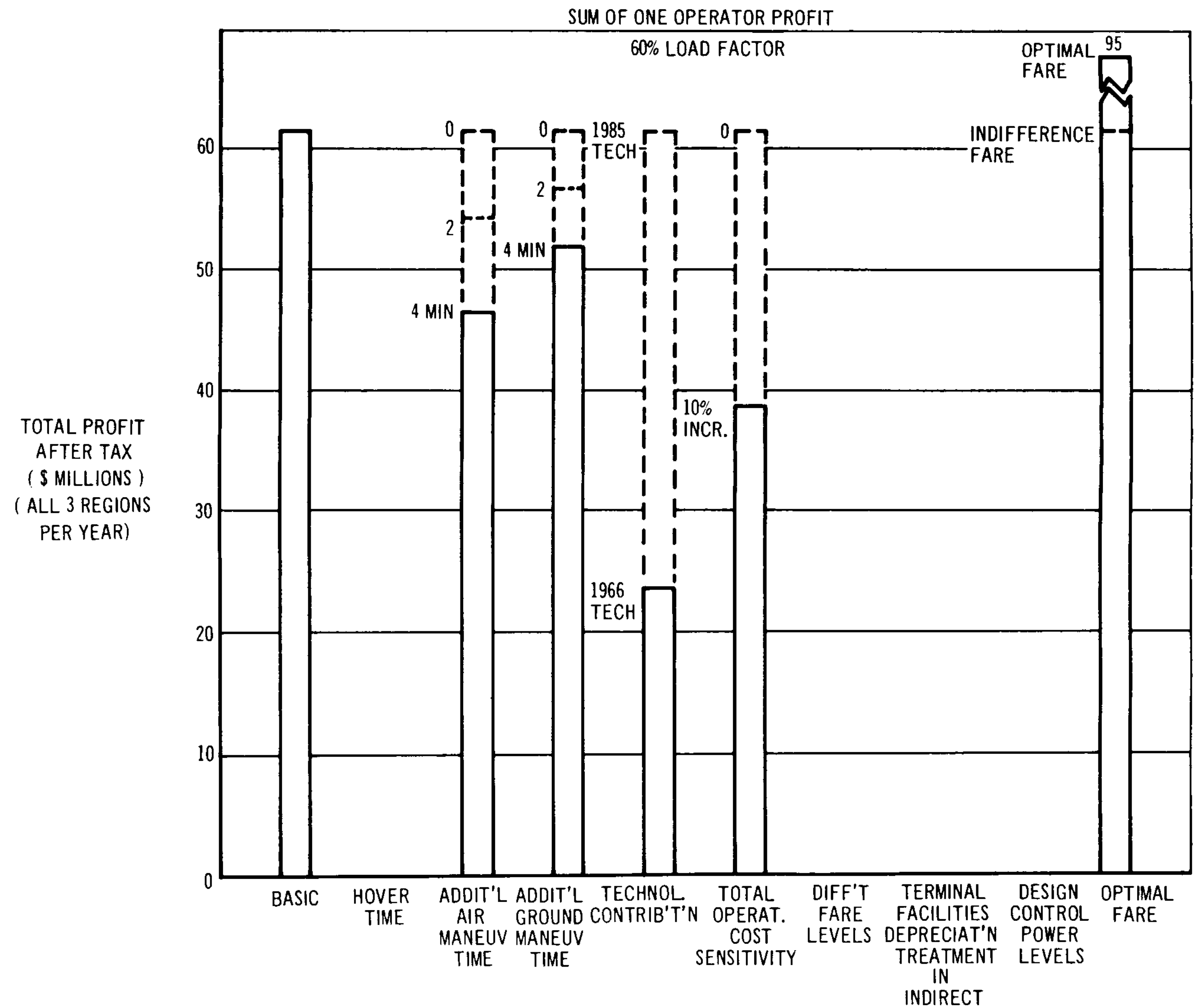


Figure 70: System Profit Concept Summary—High Lift STOL, 1650 Feet

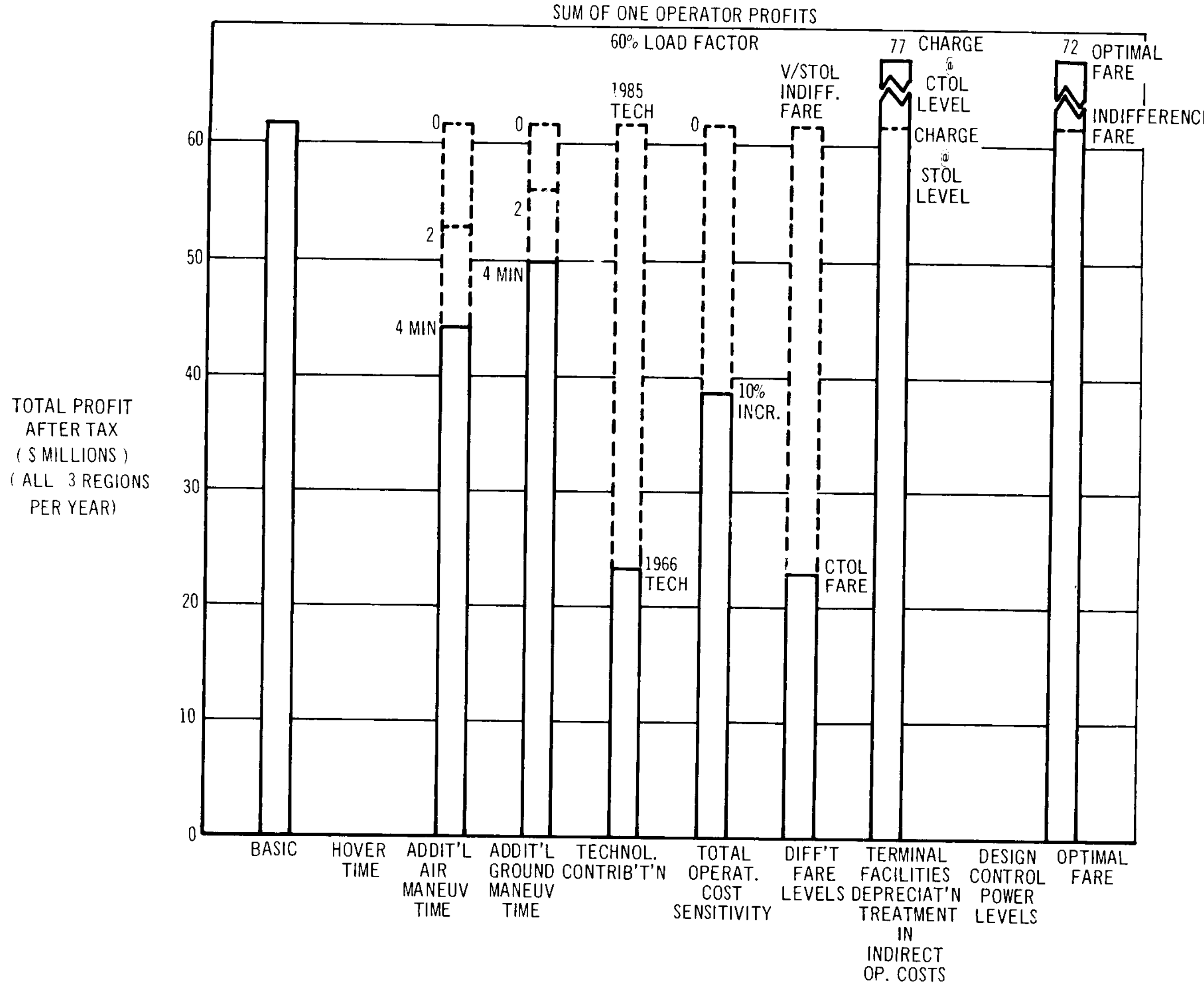


Figure 71: System Profit Concept Summary—High-Acceleration STOL, 1680 Feet

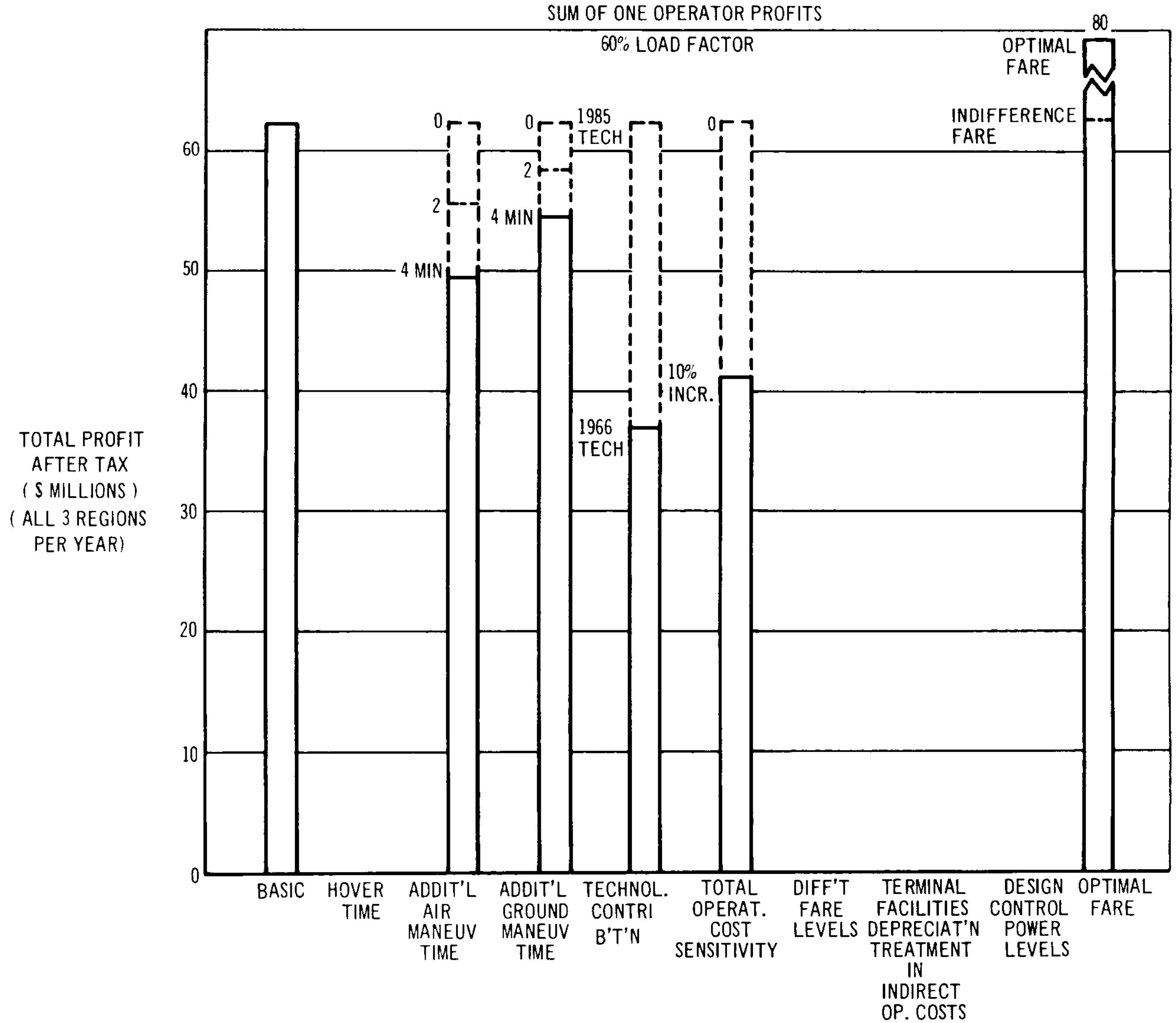


Figure 72: System Profit Concept Summary—High-Lift STOL, 2200 Feet

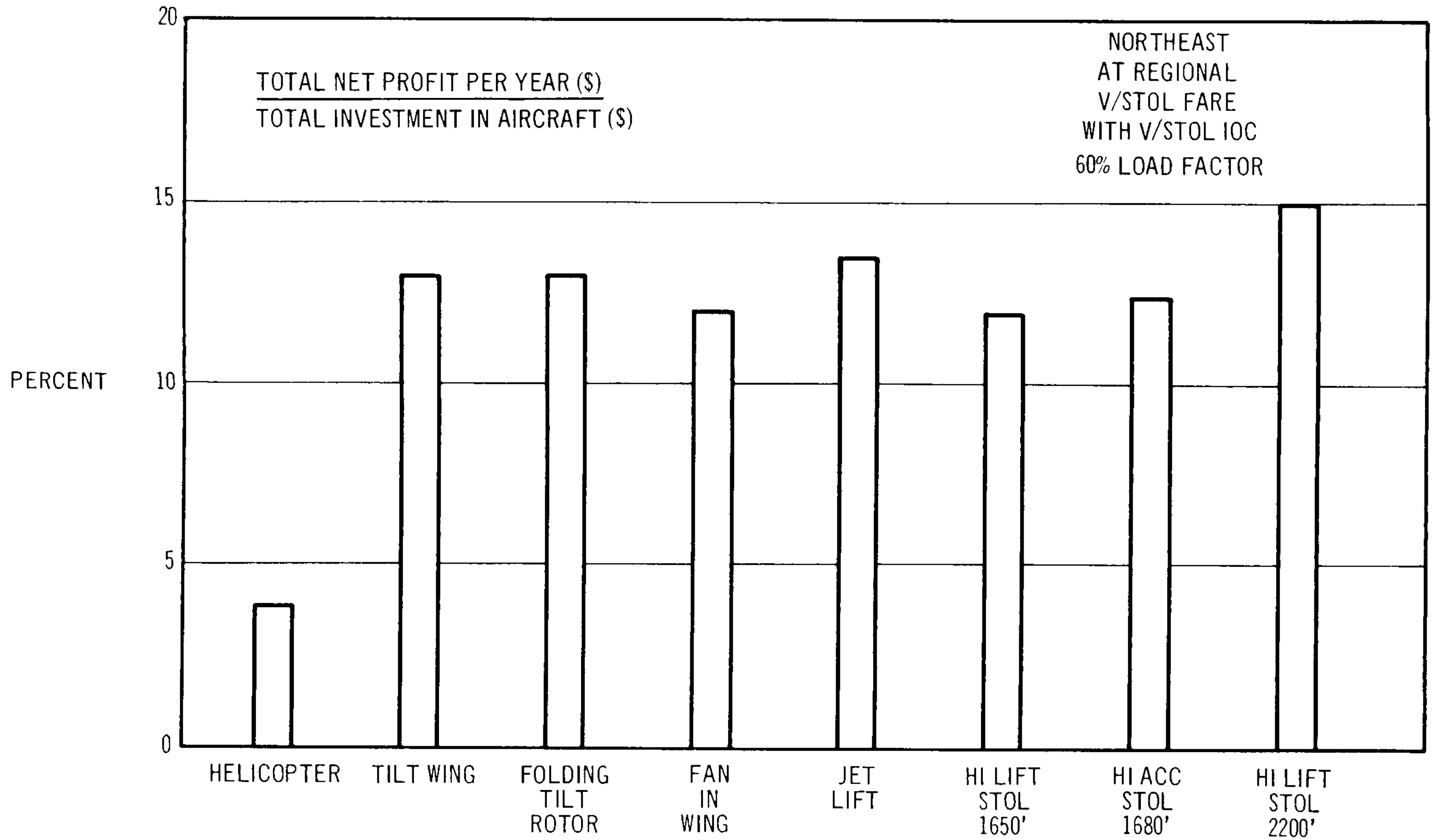


Figure 73: Profit Divided by Airplane Investment Concept Comparison—Northeast

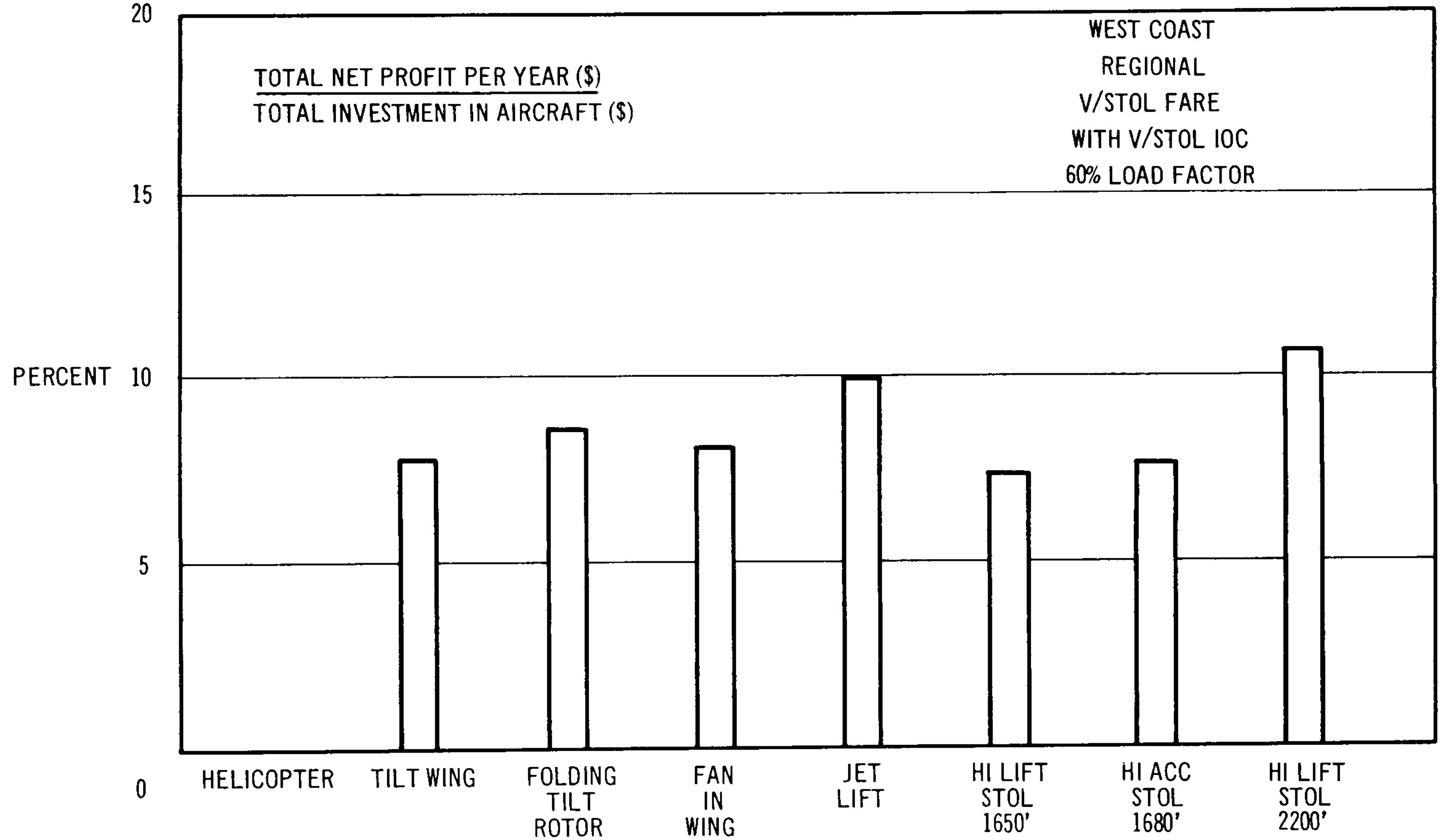


Figure 74: Profit Divided by Airplane Investment Concept Comparison—West Coast

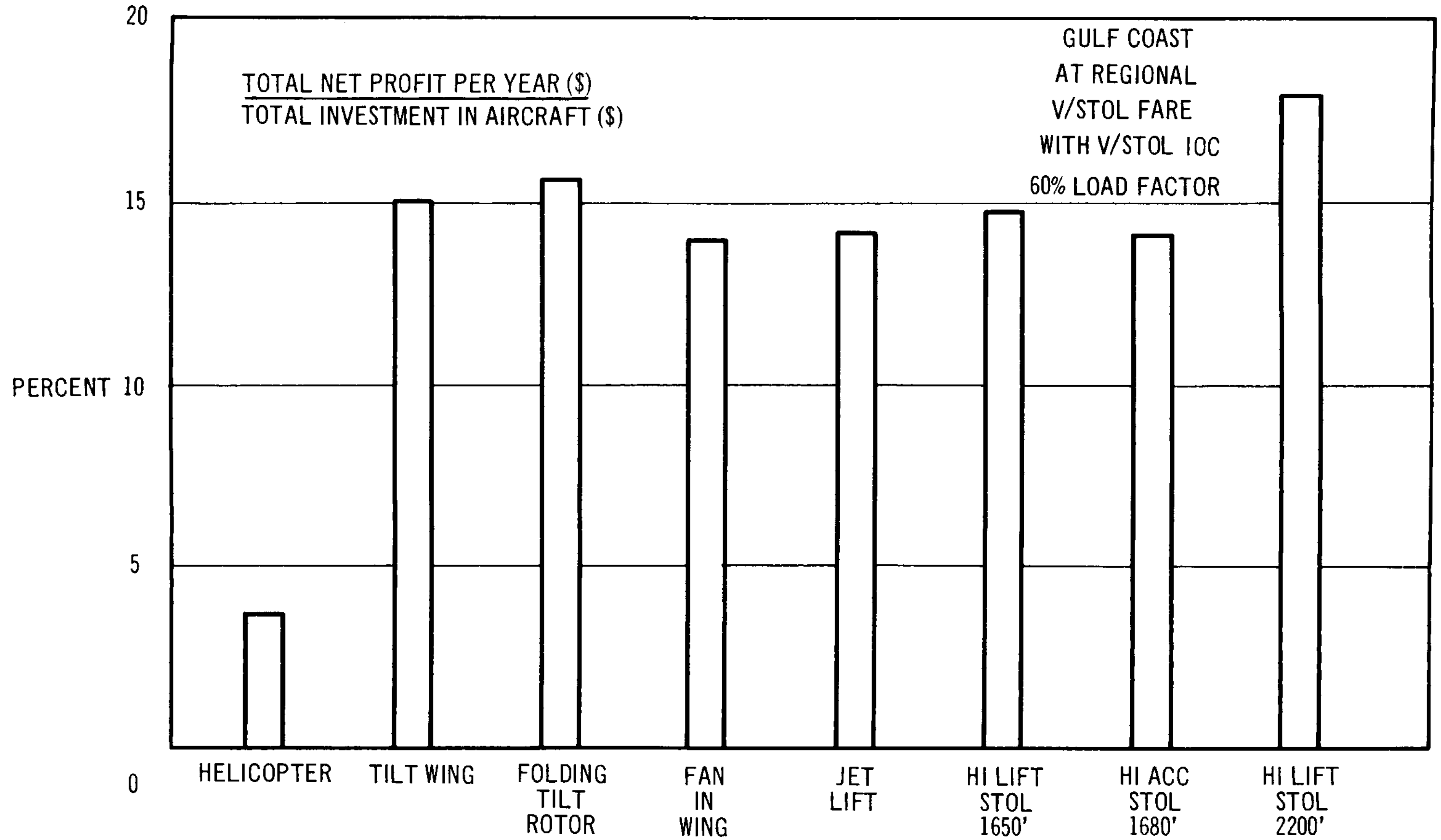


Figure 75: Profit Divided by Airplane Investment Concept Comparison—Gulf Coast

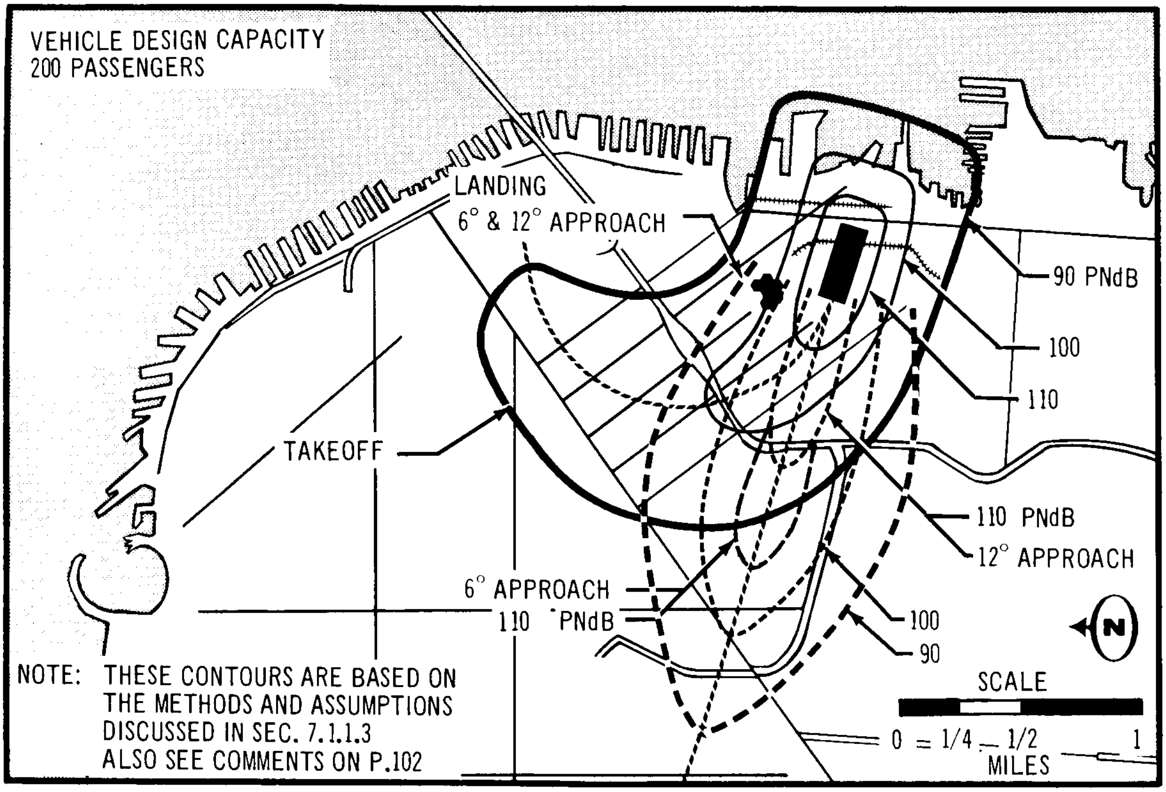


Figure 76: High-Acceleration STOL Noise Contours—San Francisco

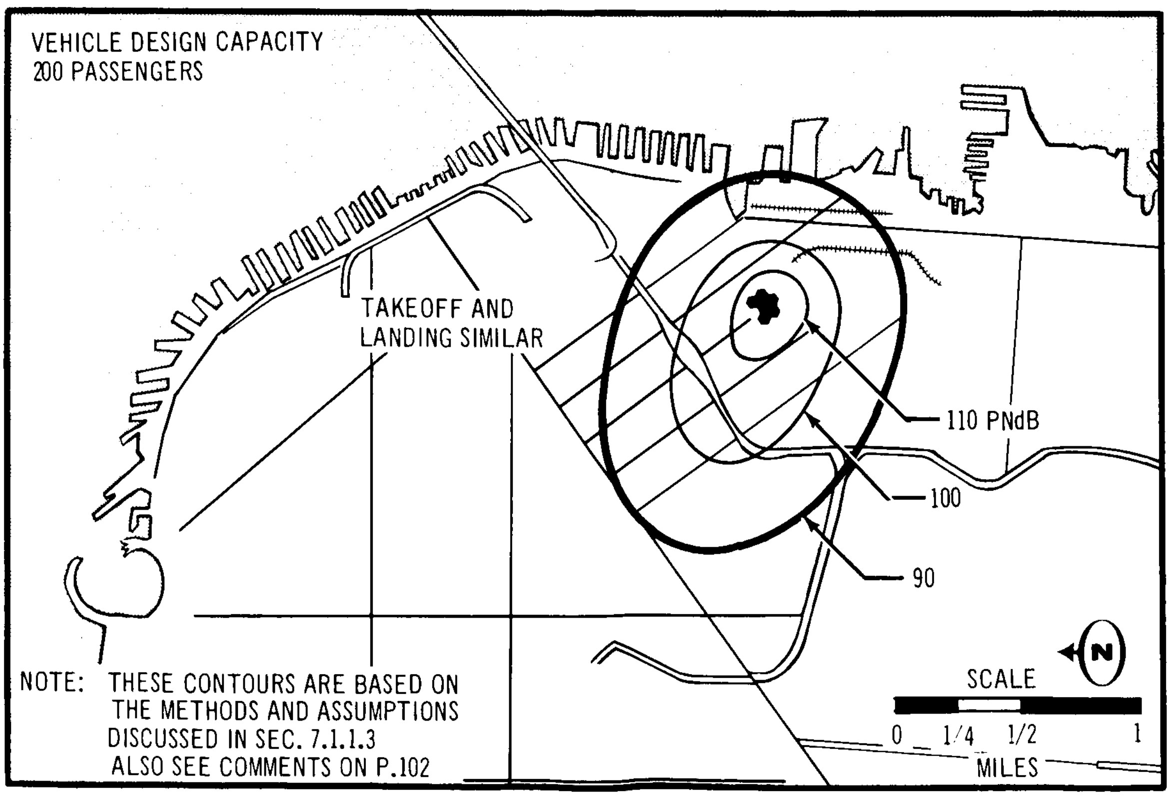


Figure 77: Jet-Lift VTOL Noise Contours—San Francisco

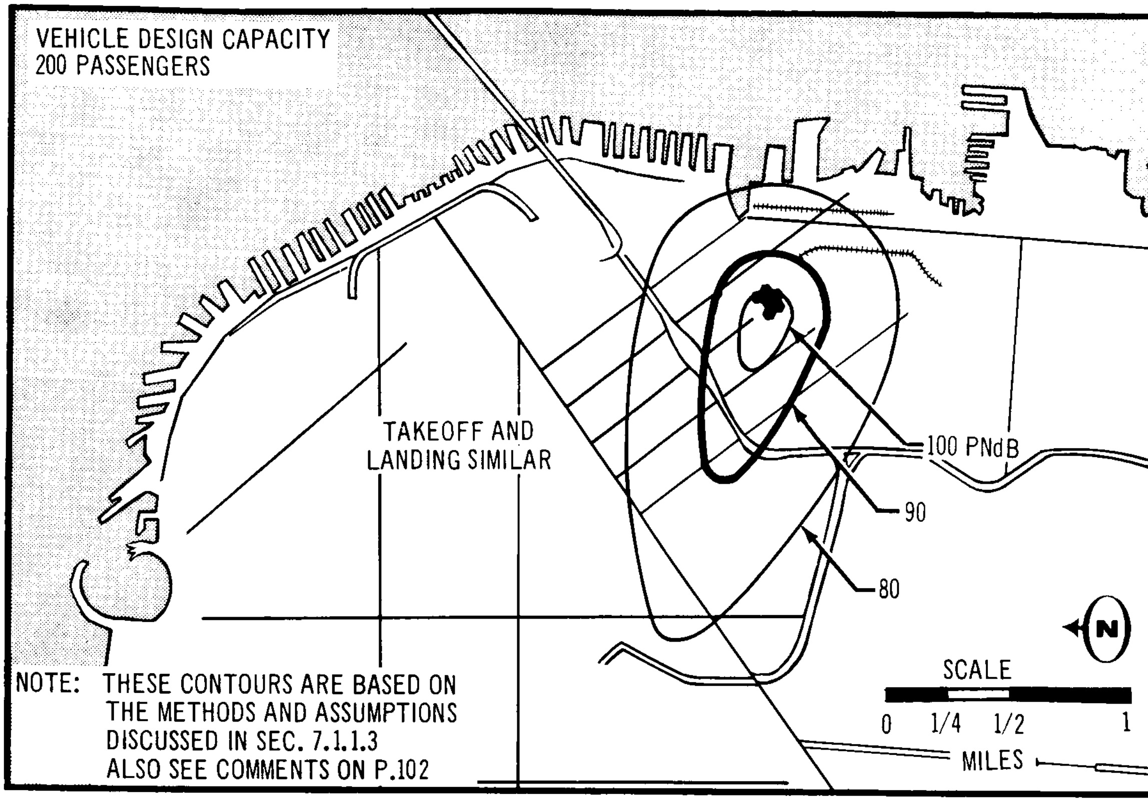


Figure 78: Tilt-Wing VTOL Noise Contours—San Francisco

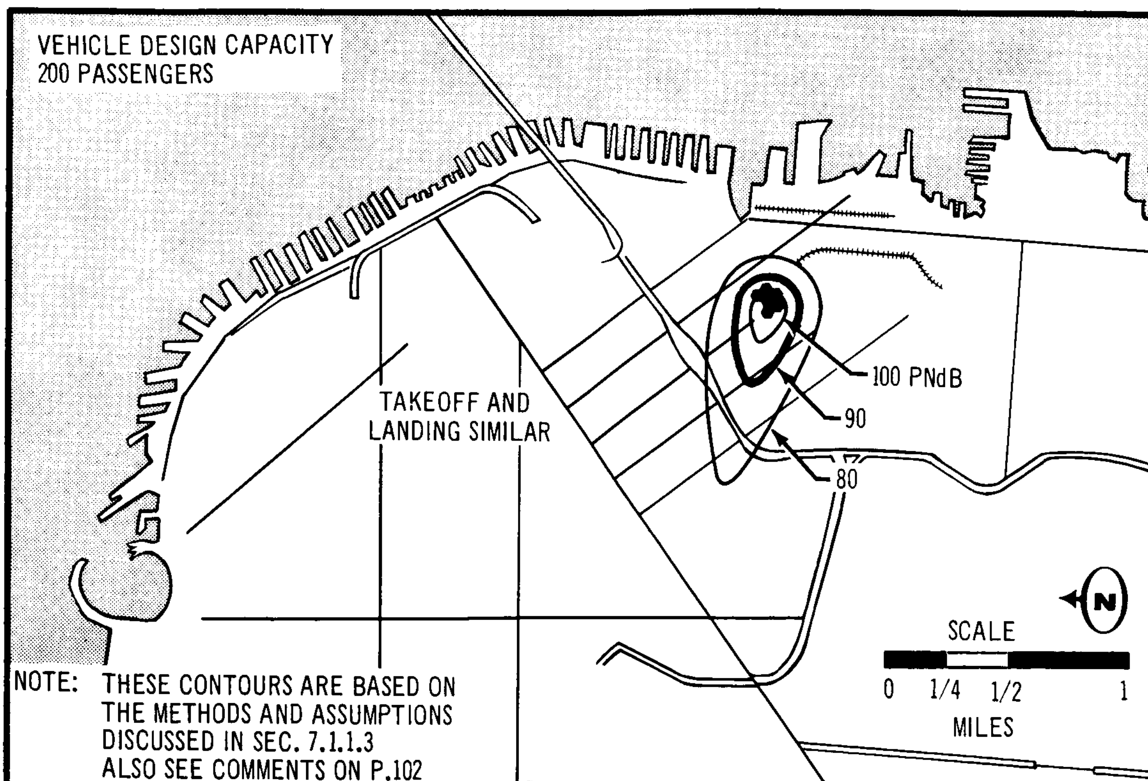


Figure 79: Folding Tilt Rotor VTOL Noise Contours—San Francisco

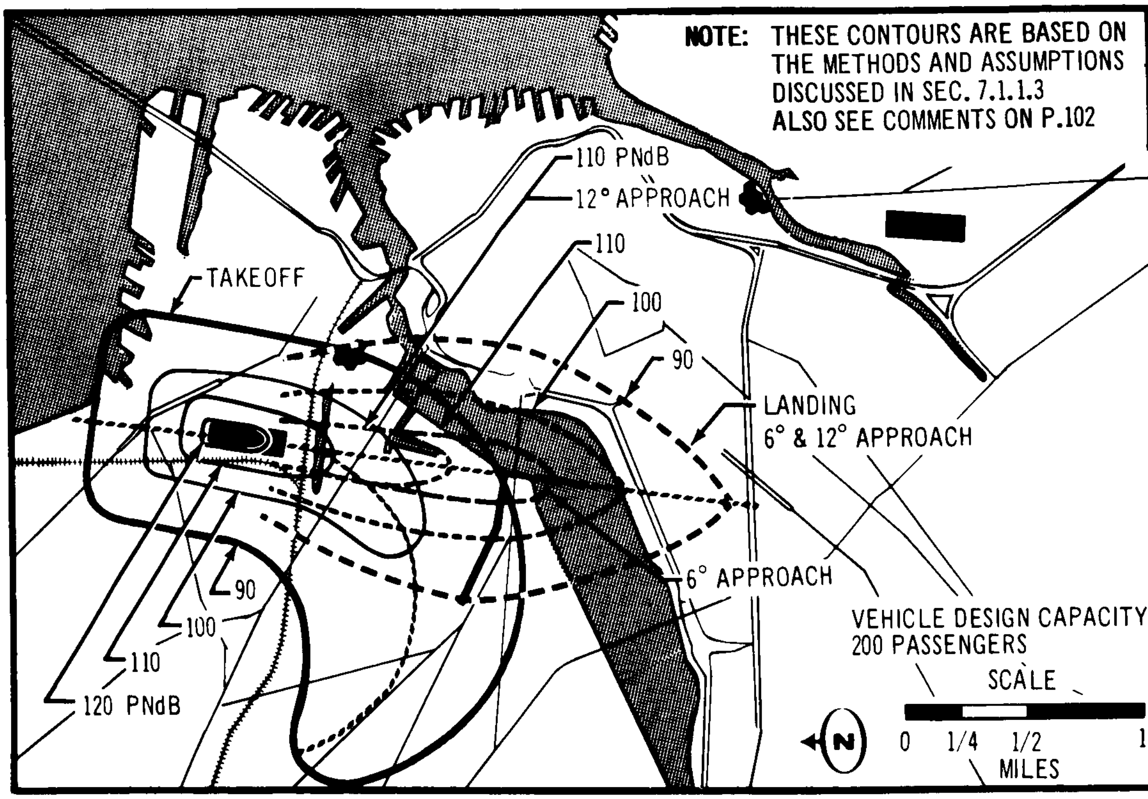


Figure 80: High-Acceleration STOL Noise Contours—Boston

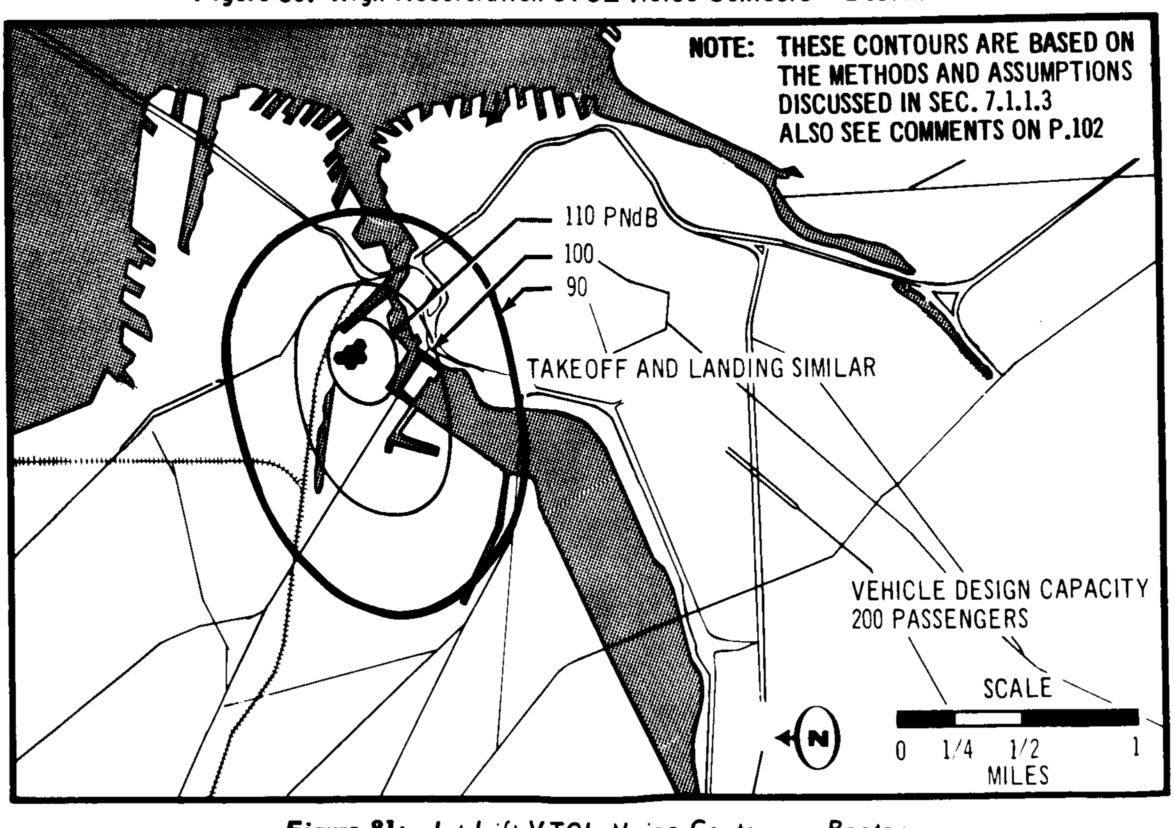


Figure 81: Jet-Lift VTOL Noise Contours—Boston

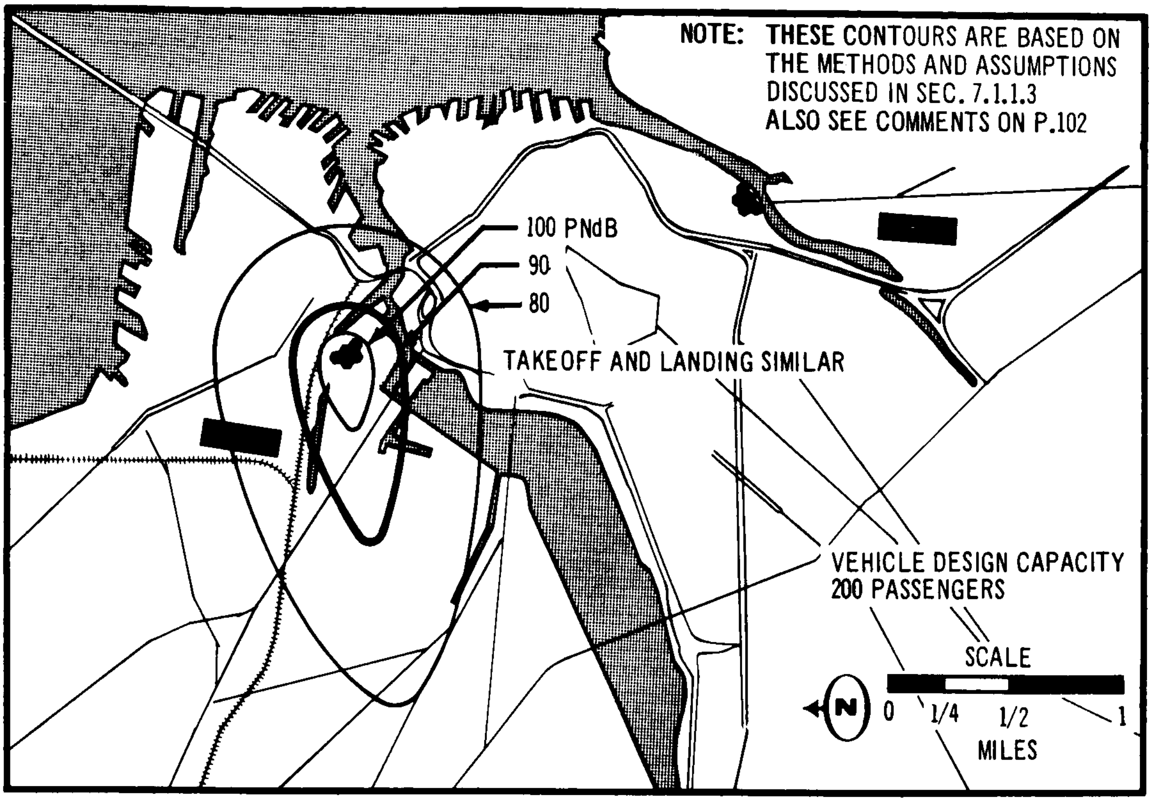


Figure 82: Tilt-Wing VTOL Noise Contours —Boston

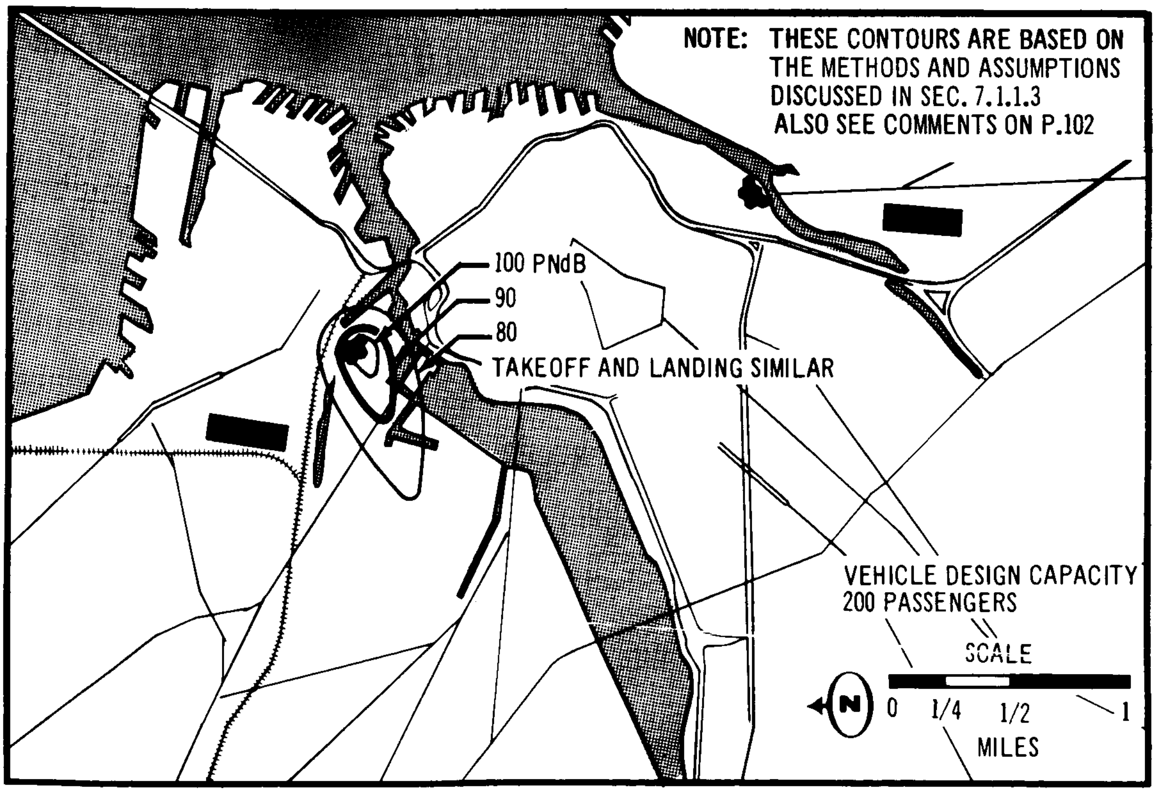


Figure 83: Folding Tilt Rotor VTOL Noise Contours —Boston

6.6.2 Community suitability. — There are many criteria to be considered as standards of community acceptability of a new transportation system. Examples are convenience to the customer, the interface with other transportation modes, the possibility of creating new surface traffic congestion, and others.

However, in the case of the particular transportation system analyzed in this study, probably the most critical criterion is noise. In this section a series of perceived noise level contours are presented that would be experienced by a sample of the cities included in the system. The locations of the terminals postulated in this study are generally compromises between a convenient location for the traffic-generating area, the least aggravation due to the additional noise generation, a possible junction of other transport modes, the existing and possible future land uses, and the avoidance of surrounding airport air corridors.

It should be emphasized that these perceived noise level contours are established on the basis of the advanced technology assumptions presented on page 18 and on the use of current methods of noise level estimation. Specific changes in current noise levels due to predicted improvements are: a reduction of 10 PNdB for the rotor concepts which reflects the elimination of the blade bang phenomenon, and a reduction of 15 PNdB for the lift and cruise engine concepts (which consists of 6 PNdB due to removal of inlet guide vanes, 2 PNdB due to increasing rotor-stator spacing, 4 PNdB due to reduction of the fan tip speed, and 3 PNdB due to acoustic treatment of the inlet).

Four configuration noise contours are shown for each city: a STOL concept and three VTOL concepts — jet lift, folding tilt rotor, and tilt wing (figs. 76 to 83). Both takeoff and landing conditions are shown. In all cases the contour is for the maneuver that exposes the smallest area of the city to the generated noise. In the STOL case, the climbing turn procedure used on takeoff to limit the noise exposure in the straight-out direction achieves this objective but creates another exposure area to one side of the runway.

Straight-out takeoff contours do not extend much beyond the landing contours, which appears to suggest two alternatives that are consistent with the noise projection in both landing and takeoff: (1) eliminate the need for climbing turn takeoff maneuvers or (2) propose landing maneuvers that involve turning descents.

It is clear, however, from these charts that the community suitability measure with respect to perceived noise is a far better criterion to use to separate the concepts than are the economic suitability measures. Using the 90-PNdB contour as a common link between all concepts, it can be seen that the folding tilt rotor affects the least area of the city, progressing through the tilt wing and jet lift concepts to the STOL concept affecting the greatest area of the city. Note that the folding tilt rotor and the tilt wing concepts show an 80 PNdB contour while the other two concepts do not.

It must not be overlooked, however, that these contours are based on current methods and assumptions of future achievements in sound suppression. Future research may produce PNdB reductions in the various concepts that will differ from those predicted today, so that it is not inconceivable that even this

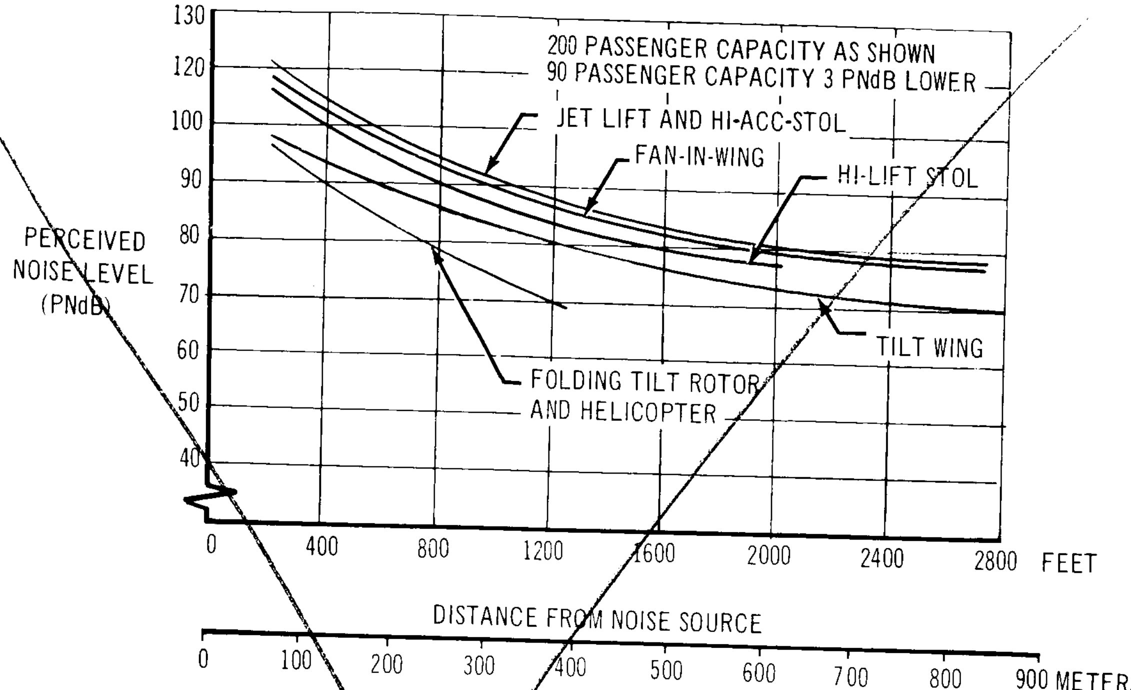


Figure 84: Perceived Noise Levels—Concept Comparison

measure of concept segregation could be nullified by the fact that noise characteristics of each lift system may be brought more nearly similar to each other.

Figure 84 also presents a comparison of perceived noise levels of each concept on a simple scale of distance from source.

When an acceptability criterion has been developed it should be possible to determine which concepts are acceptable and which are not.

6.6.3 Passenger Suitability. —This criterion is one which, while difficult to quantify in many respects, can be of significant influence in the acceptability of one concept relative to another.

Such factors as interior noise, induced vibration from either the lift or the cruise propulsion system, vertical and horizontal accelerations induced in the various flight modes of the aircraft and cabin floor angle or airplane attitudes have all been assessed during this study.

A review of interior cabin noise levels of most of the concepts produced the following essentially qualitative conclusions. Noise levels during takeoff are determined primarily by the engine noise in all the non-rotor concepts. A level of 115 db is expected as compared to the current jets with wing mounted engines of 90-110 db. Therefore, to achieve comparable interior noise levels on the non-rotor V/STOL concepts will require additional acoustic treatment. The principal source of engine noise is the cruise, lift/cruise engine or the lift engine, hence the fan-in-wing and STOL vehicles are expected to require as much treatment although of a different type, as the jet lift concept. The compartments containing the lift engines will need specific design attention. Lift engine exhaust ducts will need to be isolated from structure. Damping treatment on exhaust ducts and firewall structure and insulation blankets around the firewall will be needed to keep the lift engine ducted exhaust noises from contributing significantly to the interior sound levels.

The rotor concepts on the other hand are expected to be somewhat quieter inside on takeoff. Here the principal source of interior noise will be from the propeller or rotor, when the plane intersects the fuselage (during transition), and from the gear box and transmission. Engine noise on takeoff will not be predominant, as the majority of the energy is extracted via the transmission rather than released at the exhaust.

Interior noise in the typical high speed, relatively low altitude, short haul operation of these vehicles will come essentially from the boundary layer noise (except in the propeller plane of the tilt wing). All concepts are essentially the same, although in detail may need different treatment due to differences in local shape. However, in order to achieve the same level of interior noise as experienced in today's airplanes at M = 0.85 at 25 000 feet, the short haul concepts operating at M = 0.85 - 0.90 at 15 000 - 20 000 feet will need additional acoustical treatment.

During this study the subject of vibration has not received any quantitative analysis. It is evident from existing vehicles of the jet propelled, propeller propelled, or rotor propelled types that there are different levels of structural vibration induced, usually more severe in the rotor and propeller propelled vehicles. Thus, this study has not contributed any new visibility to the present approach of separating those concepts that exhibit rotor vibration characteristics in takeoff and cruise, those that do only in takeoff, those that exhibit propeller vibration characteristics in takeoff and flight and those that essentially exhibit gas generator vibration characteristics during takeoff and cruise.

Induced accelerations in the horizontal and vertical direction can occur in several modes of flight and with different magnitudes in each concept. In the vertical direction, probably the most significant acceleration to the passenger is that associated with ride comfort in gusty air. The subject of gust alleviation is discussed in sec. 7.1.2.6.

For equivalent ride comfort in all vehicles, substantially more gust alleviation is required by the STOL and rotor and tilt wing VTOL vehicles than by the jet lift or fan-in-wing VTOL. Alternatively, it could be surmised that for a given level of gust alleviation capability, the former vehicles will have to cruise slower, and hence be less efficient than the latter ones. In the horizontal direction, probably the most significant acceleration to the passenger is that associated with STOL landing and takeoff. The high acceleration STOL design uses substantial thrust for takeoff acceleration and landing deceleration. In the landing case, field lengths have been calculated for decelerations of 1/2 g and 1 g, on the assumption that the former is acceptable without any redesign whereas the latter deceleration is probably acceptable if the manner of passenger restraint or seat inclination is changed from today's methods. Acceleration in takeoff is of the order of 1/2 g, not much different from the conventional airplanes capability at light weights today.

In transition and steep descent flight paths, fore and aft acceleration is limited to 0.15 g.

It would appear then that a judgement of concept suitability from the passenger's viewpoint would conclude that, if the criterion is to be low noise, low vibration, smooth ride in cruise, and no excessive accelerations in any direction, the choice will be weighted in favor of the high wing loading, large wing sweep, non-rotor, VTOL concepts.

7.0 ANALYSIS

The analysis for this study is generally divided into two broad fields of investigation:

- Advanced technology and configuration determination
- Market determination and vehicle and system analysis

It is necessary to establish a level of technology in each design discipline that can be considered available for production aircraft in use in 1985.

It was decided that the period under review (1985) should be considered as one in which the operator had already completed the introductory period of these new aircraft.

Thus the following dates are established:

1983	Initial introduction of aircraft into service
1982-1983	Aircraft certification
1980	Propulsion system go-ahead
1980-1982	Propulsion system technology
1982	Propulsion system FQT (flight qualification test)
1981-1982	Aerodynamic technology
1981-1982	Structures, materials, and manufacturing technology
1980-1982	Navigation and flight control technology

This allows a period of approximately 15 years from 1966 to establish the levels of technology that are used in this study. A discussion of these technology levels in each design discipline follows in the next section.

Similarly it is necessary to establish airline systems with traffic demand data as representative as possible of the 1985 time period in this intercity, short-haul market.

Consequently, the remaining sections of the analysis cover the establishment of the cities to be considered, the forecast of traffic demand and traffic flow, and the interrelation of these factors with the economic aspect when the distribution of traffic by concepts has been determined. Operating costs are also defined and determined. Finally, the system is explained, and the results of exercising certain selected concepts and configurations in these systems are discussed.

7.1 Technology and Configurations

7.1.1 Determination of advanced technology. —The RFP and the proposal (Boeing document D6-60014) generally determined the concepts to be studied.

It was necessary at the start to clarify the definition of particular concepts to orient the determination of the advanced technology level.

The Vertol Division was required to investigate 1985 derivatives of tilt-wing and compound-rotor aircraft.

The compound-rotor aircraft group is assumed to encompass a spectrum of aircraft that ranges from the pure helicopter through the semicompound or compound configurations having propulsion and/or lift unloading to the convertible aircraft using a rotor system for hover and low speed flight. The rotors in these latter configurations are folded and stowed for cruise flight at speeds well in excess of the capability of the compound helicopter. This speed, and therefore increased productivity, is obtained at the expense of a considerable increase in aircraft size for a given payload/range capability; it is therefore not a foregone conclusion that the faster aircraft will have the lowest direct operating cost. It was therefore decided that the two ends of the configuration spectrum should be investigated. Accordingly, pure helicopters with advanced rotor systems and aircraft with stowed rotors are studied. Propulsion and lift unloaded configurations were not examined since Vertol Division trend studies indicate that these types offer no great advantages over the pure helicopter or stowed-rotor aircraft.

Because it is not possible to examine a complete spectrum of tilt-wing related aircraft within the scope of the study, it was decided that two concepts would be studied. These are the now conventional high disc loading tilt wing, and an advanced concept that combines high cruise speed capability and even more improved noise, downwash, and fuel flow characteristics in hover than the conventional tilt wing. The advanced concept can best be described as a convertible version of a tilting rotor aircraft. The transition sequence is identical to that of a tilt rotor. However, the aircraft is powered by convertible fan engines (i.e., capable of producing shaft power or fan thrust) and has rotor blades that can be folded back into wing tip nacelles. Therefore, following transition a conversion sequence occurs in which propulsive thrust is transferred from the rotors to the fans, and the rotor blades are stopped, feathered, indexed in azimuth, and folded. This folding tilt-rotor concept is covered by patent application and was developed prior to this NASA contract.

Development of the convertible fan engines is required for the folding tilt rotor and stowed rotor aircraft, this principally being an integration of proven components. All of the rotor-driven aircraft will require development of engines of greater power than those currently available and the drive systems to handle this additional power. However, as the following table shows, the drive system torques and rotor sizes are not beyond present and projected values. Only the convertible fan engine powers are greater than present shaft engine powers, but even these engines would be derived from turbofan engines smaller than the engines under development for the C-5A and Boeing 747.

Type	Power (SHP)	Max torque per gearbox (ft-lb)	Rotor RPM	Rotor or propeller diameter (ft)
Present				
MI 10	2 x 5000	4.5×10^5	116	115
TU 114	4 x 15 000	7.32×10^4	1075	16
Projected				
Sikorsky heavy lift helicopters***	4 x 20 000**	5.65×10^6	75	180
Study Aircraft — 200 Passengers				
Tilt wing	4 x 12 300	1.166×10^5	555	29.2
Folding tilt rotor	2 x 34 400	4.9×10^5	235	67.4
Stowed rotor	2 x 41 300	1.09×10^6	149	92.0
Helicopter	2 x 6010	2.09×10^5	150	93.6

** Shaft version of P&W J 52
*** Source: Aviation Week 1/23/67

NOTE: SHP x 0.746 = kw; ft-lb x 1.356 = m-N; ft x 0.305 = m

The basic tilt-rotor concept has been extensively investigated in the XV-3 program. The major problem encountered, tip path plane instability, is less likely to affect the folding tilt rotor since rigid, noncyclic rotors are used. Other tilt rotor problems that would be encountered at high speed include the whirl mode/flutter case encountered with rotor/wing combinations. Here again, the folding tilt rotor is less likely to be affected because of the relatively low (185 kn, 95 m/sec) V_{NE} in the rotor mode.

The major items requiring investigation are rotor folding and the hover yaw and pitch control using deflected fan thrust. The rotor folding sequence consists of feathering and stopping (which are now routine operations), indexing to the required azimuth position, and folding back into nacelles. None of these are formidable tasks, but development of the folding mechanism is required, and the transient conversion handling qualities must be investigated. The hover yaw and pitch control should be a straightforward development process based on present technology for thrust reversal and deflection.

The technical feasibility of the tilt wing concept has been firmly established by the three prototypes flown to date. The first tilt wing, the VZ-2, was a somewhat crude research aircraft intended to demonstrate the feasibility of the concept. However, it was eventually used to provide tilt wing experience for many pilots. The more sophisticated CL-84 and XC-142 aircraft are the other two prototypes.

The major area for research and development for the tilt wing concept proposed in this study is the monocyclic pitch control system. Full-scale testing is required in hover and low-speed flight to determine the limit of control power obtainable and to provide complete stress, aerodynamic, and dynamic load data. Full-scale propeller hubs and control system hardware also need to be developed. This should include the development of large-diameter, lightweight propeller blades. Although the limits of monocyclic control are not known with absolute accuracy, it is likely that such control may not be sufficient for aircraft of high gross weight. This is because propeller diameter does not grow as fast as the square of pitch radius of gyration. Therefore, monocyclic control, which effectively offsets the thrust radially by a fixed amount, provides a decreasing pitch acceleration capability as gross weight increases. Because of this phenomenon, research is also required into augmentation of monocyclic control with flaps or wing tilt coupled to longitudinal stick motion. Boeing analysis has shown that a combination of monocyclic and wing/flap control can provide sufficient control for tilt wing aircraft of the largest size described in this report. The transition performance trim and stability characteristics of the tilt wing are now well understood, and future aerodynamic testing will be confined to detailed development of specific configurations. It has been assumed that the tilt wing design presented here is able to combine a wing loading of 100 lb/ft^2 (488 kg/m^2) with a disc loading of 50 lb/ft^2 (244 kg/m^2). With present technology this would result in wing stall problems during descent and deceleration. Future research should be directed towards freeing the present dependence of wing size on propeller diameter. This may be accomplished by relative tilting of the propeller thrust axis and wing chord line to control stall in transition during descent and deceleration, or boundary layer control may be used for this purpose. However, these devices might incur further research requirements to obviate any handling qualities problems they may cause. Development of fly-by-wire control systems is of particular interest to the tilt wing configuration. Phasing and mixing of control system functions and transference of control motions across the wing tilt axis could be accomplished electrically at a great weight saving. Such a system would permit any desired level of control breakout forces and stick forces to be incorporated, and stability augmentation systems and automatic landing systems could readily be integrated with the control system.

The stowed rotor aircraft is a comparatively recent development. Some exploratory wind tunnel tests have been made.

The major problem area is the conversion process. It is necessary to study the mechanical, dynamic, aerodynamic, and stress problems associated with stopping, folding, and stowing the rotor blades and the reverse process of deploying and spinning up the rotors. Stability during the conversion requires investigation, and the phasing and mixing of the helicopter and conventional flight control systems must be determined. The conversion is fundamentally more difficult than that of the folding tilt rotor, since both lift and longitudinal force must be transferred after attaining conversion speed. The folding tilt-rotor lift transfer takes place during the tilt-rotor mode transition, leaving only thrust to be transferred at conversion speed.

A major item of research and development for the helicopter is the rotor system. Analytical and some experimental work has been done on advanced rotor systems incorporating boundary layer control or the lift offset principle. However, to solve the structures and mechanical problems of such systems, considerable effort will be required concurrent with aerodynamic research and development.

Of major concern to the nonrotor VTOL concepts is the development in technology that can be achieved in the propulsion systems to reduce the weight, size, and noise of the units. However, some configuration-oriented developments are necessary that are difficult to quantify in terms of a level of technology improvement.

An extensive research, test, and development program is assumed to be necessary to solve the stability and control problems of a configuration that is susceptible to the interaction problems of aerodynamic and propulsion airflow mixing.

For the STOL and CTOL concepts, the specific technology improvements to be determined are in the areas of high-lift flaps and low-speed control and stability. For all concepts, advanced levels in technology to be determined are those associated with high-speed cruise drag reduction, the use of high-strength, lightweight structural materials, and the development of lighter and smaller powerplants.

7.1.1.1 Aerodynamics. — The principal areas in which technology advances or design developments are expected are:

- Cruise drag reduction
- High-lift flap development
- Powerplant-airframe integration
- Stability and control
- Rotor design
- Rotor solidity

Cruise Drag Reduction

Studies show that by 1985 the drag of the basic airframe due to skin friction will be reduced by 6% of the minimum profile drag coefficient. A further reduction of 3% will be obtained by better control of surface quality and excrescences. A reduction of 1% will be obtained from refinement of wing, nacelle, empennage, and body intersection shapes, thus accounting for a predicted 10% reduction in profile drag coefficient.

Paralleling the reduction of drag will be an increase in cruise lift coefficient and cruise Mach number. Figure 85 shows the improvement in drag rise expected at a given C_L and wing configuration when these effects are incorporated.

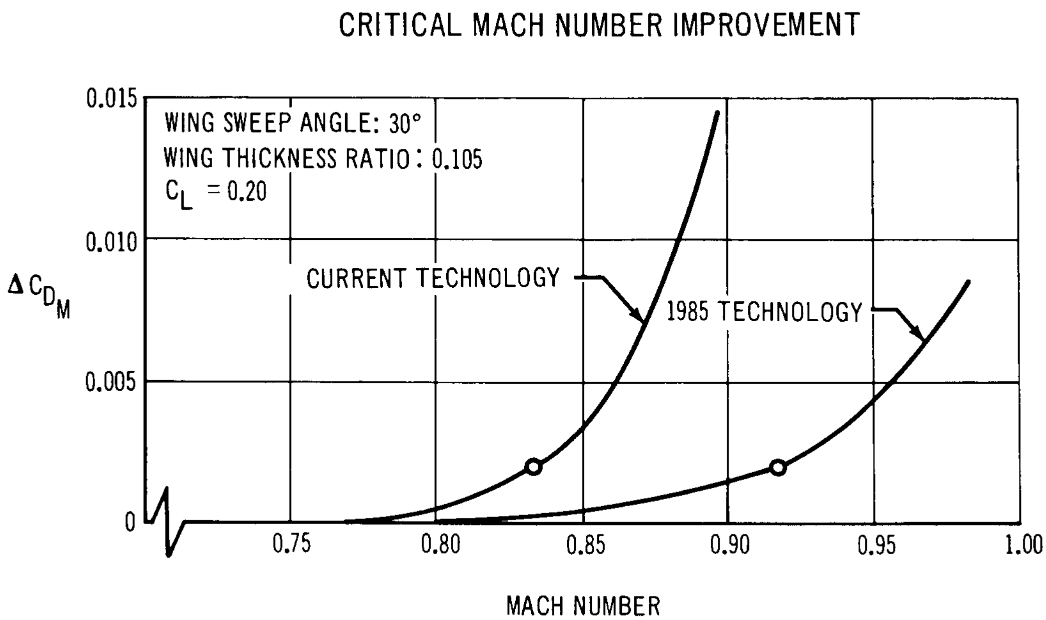


Figure 85: Critical Mach Number Improvement

The aerodynamic developments that are expected to result in these improvements include:

- Extension of the laminar region of airfoils by detailed mathematical analysis of the pressure distribution and the consequent shaping of the airfoil sections. Computer techniques enable many airfoils and very small increments of surface contour to be analyzed.
- Design of transonic wing sections with partial areas of shock-free supersonic recompression allows a higher section Mach number for the same (or higher) L/D than experienced today. Again, computer applications of theoretical analyses of boundary layer separation and control of shock wave strength are the tools used. These computer programs treat wing design, both with and without the fuselage interaction.

In addition to the reductions in drag predicted for the fixed-wing concept in the appropriate areas, the helicopter will benefit by new drag reduction techniques in the area of the rotor hub. Experimental work on the application of boundary layer control to reduce rotor hub and pylon interference has recently been undertaken at Vertol. It is anticipated that a reduction in pylon and hub drag of 50% will be realized by eliminating the area of separated flow on these components.

High-Lift Flap Development

Considering the development in high-lift technology in the last decade, a level of low-speed lift coefficient has been predicted for the 1985 high-lift STOL concept. It is considered to be a good compromise of the many factors involved, viz., the level that is theoretically possible and a system that is not too expensive to manufacture, not too expensive and time-consuming to inspect and maintain, is relatively simple and hence reliable, and provides a good match between landing and takeoff requirements.

The flap system proposed is a full-span, triple-slotted mechanical flap with leading edge devices. Cruise powerplants of high bypass ratio are positioned on the wing so that an extra increment of lift can be attained from the external blowing feature of the engine efflux. The system thus provides boundary layer control on the upper surface of the flap, and also thrust deflection and supercirculation characteristics from the jet flap effect. The angle of the aft portion of the flap is varied to create drag changes with small accompanying lift changes as a means of flight path control.

With a four-engine configuration, the loss of thrust from one engine, contrary to what might be expected, results in only a relatively small lift loss and easily controllable roll and yaw moments.

The $C_{L_{max}}$ values for landing and takeoff are 6.7 and 5.5, respectively.

Powerplant Airframe Integration

The location of the powerplant is intrinsic to the problem of obtaining good performance and stability of VTOL machines and somewhat less so with STOL machines. This is because the thrust-to-weight ratio is slightly greater than unity compared with approximately 1/3 for conventional aircraft. Hence, the possibility of the thrust overpowering the aerodynamic forces on the controls is that much greater. This is presently a severe problem for which no obvious solution is foreseen beyond a process of continuous investigation and refinement, using the wind tunnel as the principal tool.

The flying qualities necessary for near-ground maneuvers, i.e., docile behavior and rapid response, will be developed by:

- Testing of large-scale powered models in large wind tunnels
- Simulation studies of the airframe/propulsion system
- Solving the reingestion problem by testing models of a type similar to the above in static test rigs.

In high-speed cruise the powerplant location has an important effect on drag because of its influence on the shock pattern and the interference drag. In 1985, powerplants will be relatively much smaller, so that the drag rise and higher drag levels caused by the interference of the cruise nacelles with the wing will be virtually eliminated.

Stability and Control

No detailed analysis or simulation studies have been undertaken for this program. Several wind tunnel tests have been performed recently on VTOL and STOL models by Boeing. For VTOL machines, the large-scale tests of powered models indicate that severe interaction can exist between the vertical lift propulsive forces and the aerodynamic forces, which can give rise to unstable conditions in the transition region. This problem is very much configuration-oriented and difficult to analyze theoretically. However, the problem is not considered to be insurmountable, but rather to be one of the principal areas of investigation in the development of VTOL machines.

Consequently, a quantitative measure of the advance in technology is difficult to establish in this discipline. For this study, the attitude control requirements in acceleration are therefore applied with the understanding that each concept configuration will have been analyzed and model-tested sufficiently by the 1980's that this instability is eliminated or reduced to a level where an insignificant demand on the control system results.

Rotor Design

Considering potential benefits that may be expected from various high-lift rotor systems utilizing BLC (boundary layer control) jet flaps and/or possibly large flapping offset, a forward flight operating limitation of 0.7 advance ratio and 1.0 advancing tip Mach number was selected for the 1985 time period.

Beyond this limit, installed power tends to become excessively large, and the rotor rpm is lowered by the advancing tip Mach number limit, resulting in unrealistically low engine rpm as a percentage of optimum.

At an advance ratio of 0.7, ideal theory predicts an L/D_E of approximately 30 as shown in fig. 86 and noted as trend A. Trend C shows the maximum L/D_E obtained with current technology rotor systems. Trend B shows the level that is judged to be a reasonable estimate for the 1985 time period. It is a level halfway between the ideal theory and that of the present. The minimum rotor drag shown in fig. 87 is for the incompressible case and is used, together with the nonuniform downwash corrections to induced drag in fig. 88 to construct the trends of fig. 86. The induced drag corrections are based on the data contained in ref. 1.

Since an advancing tip Mach number of 1.0 is selected as the upper limit, trend B in fig. 86 is adjusted for compressibility effects. Figure 89 illustrates experimental model whirl test data for an advance ratio of 0.42. These data are extrapolated to an advancing tip Mach number of 1.0, the design level. The source of these test data is found in ref. 2. These data are then superimposed on theoretical compressibility trends of $D_{E_{min}}/qd^2\sigma$ versus μ for various tip Mach numbers and extrapolated along those shapes. Figure 90 summarizes the effects of compressibility on the minimum rotor drag as shown in fig. 86.

Finally, trend B corrected for compressibility is shown in figs. 91 and 92, and indicates an L/D_E of 14.6 and a corresponding C_T/σ of 0.261 respectively to be acceptable rotor design parameters for the 1985 time period.

Rotor Solidity

Low rotor solidity values are of particular importance to vehicles that employ rotor folding or stowing because the chord of the blades dictates the size of the body or protuberance designed to house the retracted rotors. Since it is undesirable to increase the complexity of rotors on convertible aircraft by the installation of boundary layer control systems, any improvement in reducing solidity must come from improved section lift characteristics that allow higher design lift coefficients to be used. For a rotor, a commonly used measure of usable lift coefficient is the design C_T/σ , i.e., thrust coefficient/rotor solidity. Current maximum values range from 0.1 for rotors with cyclic pitch to 0.12 for rotors that provide thrust only and have no control function. These values can be increased somewhat for high disc loading rotors of 25 to 30 psf (122 to 146 kg/m^2) and above because the stiffer blades can employ cambered sections. It is difficult to forecast the improvements that can be expected in airfoil section lift characteristics over the next 18 years since, unlike compressibility drag, little research on airfoil sections has been directed toward improving these characteristics. Therefore, few historical data exist on which to base a forecast. For this study, it is assumed that design C_T/σ values of 0.12 for cyclic rotors and 0.15 for noncyclic rotors can be used.

It should be noted that while the helicopter has a rotor boundary layer control system, a hover C_T/σ of 0.12 has still been assumed to avoid increasing hover power requirements. This assumption does not impose any constraint on the helicopter design.

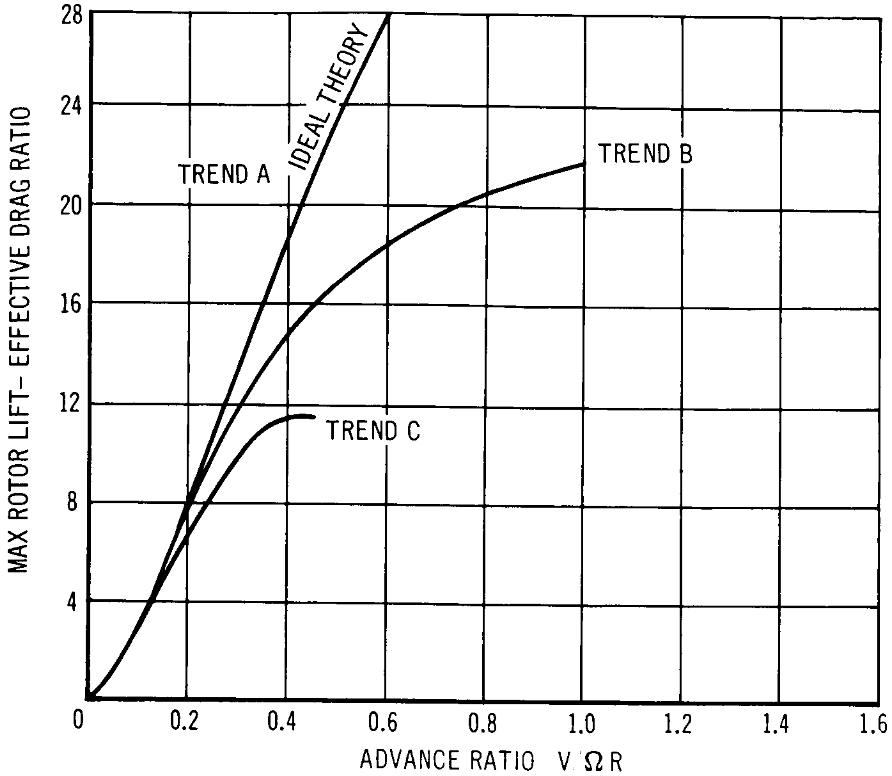


Figure 86: Rotor Lift Effective Drag Ratio

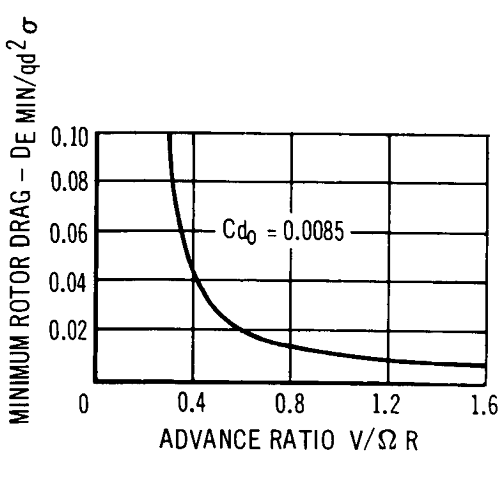


Figure 87: Minimum Rotor Drag

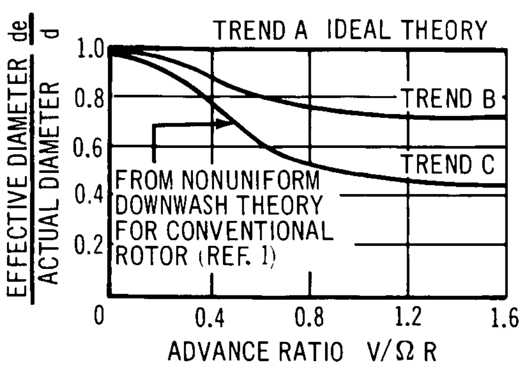


Figure 88: Rotor Downwash Corrections

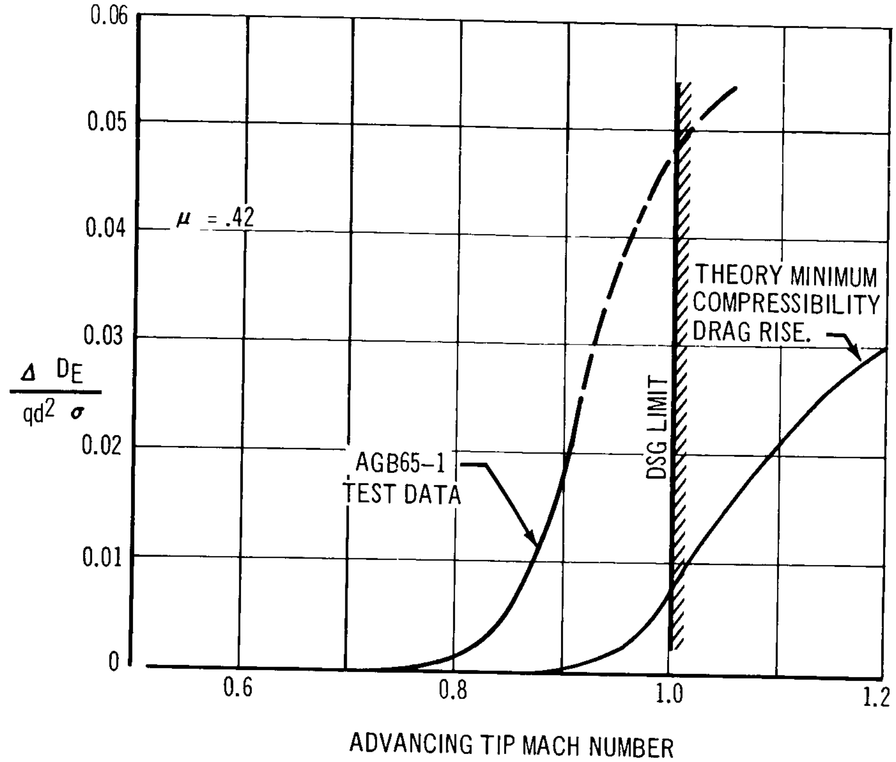


Figure 89: Compressibility Effect on Rotor Effective Drag

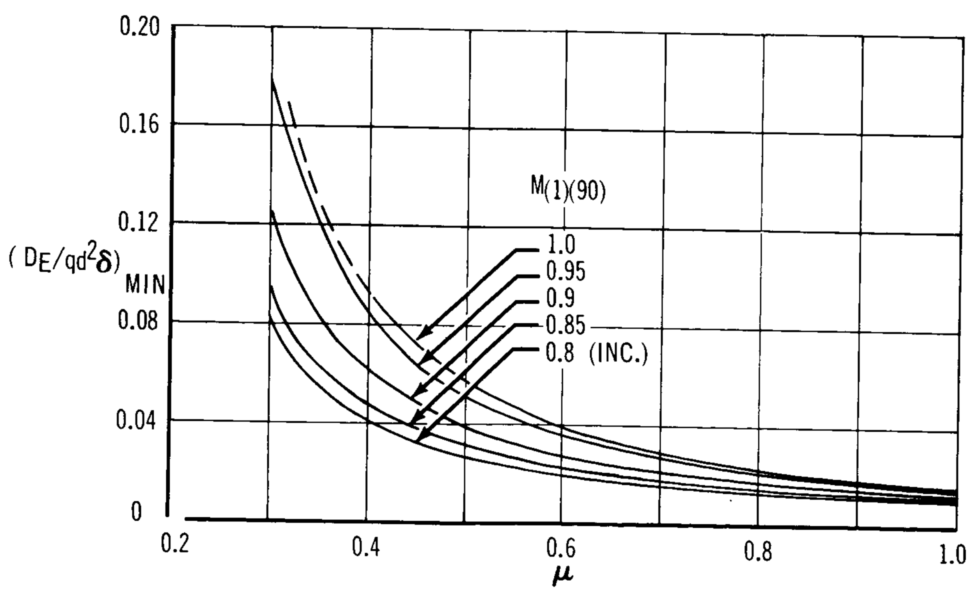


Figure 90: Effect of Compressibility on Minimum Effective Rotor Drag

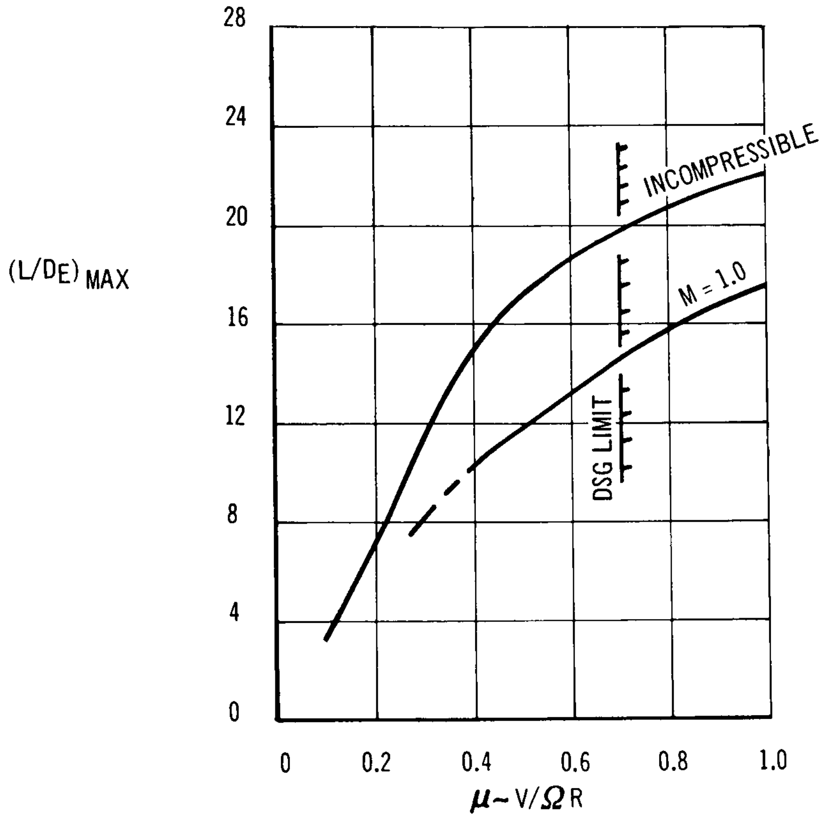


Figure 91: Compressibility Effect on Ideal Rotor L/D_E

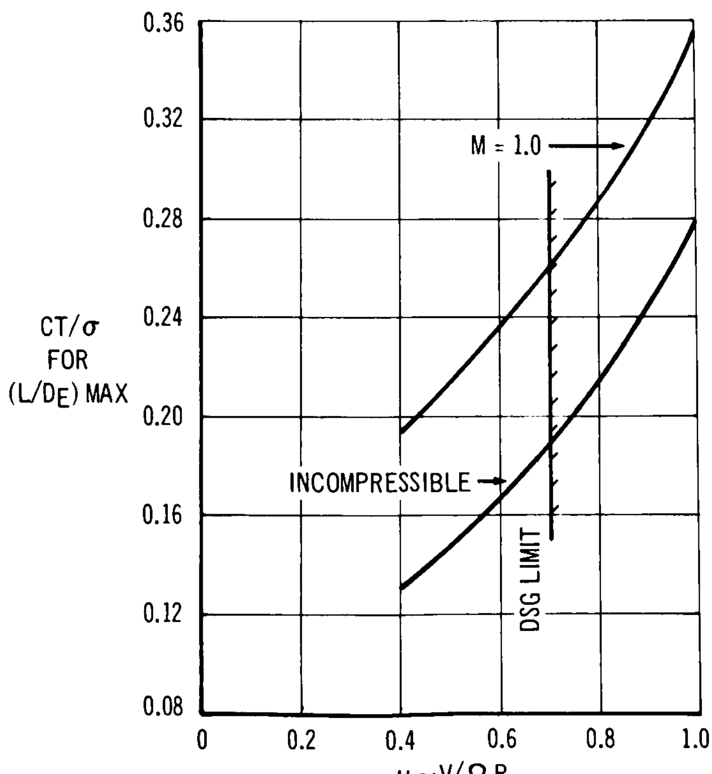


Figure 92: Compressibility Effect on Vertical Lift Force Coefficient

7.1.1.2 Propulsion. — Improvements in propulsion systems between 1966 and 1980 will result from increased turbine inlet temperature, bypass ratio, overall compressor pressure ratio, and reduction in weight. Currently it is possible to estimate the weight and dimensions of an engine with a given thermodynamic cycle by correlating its thermodynamic variables with those of a number of hardware items and proposed engines.

By 1980, technology advances will permit construction of lighter engines. The amount of reduction that can be expected will vary for the different engine types (see fig. 93). Significant reductions can be expected in cruise engine weights because of high competition among the various engine manufacturers, which can be expected to continue. Similarly, there has been considerable effort in the development of lift turbojets and turbofans. However, there has not been a development program of the same magnitude for remote coupled lift fans, so changes that can be expected will be comparatively less.

It is anticipated that trends towards increasing stage pressure ratios, overall pressure ratios, bypass ratios, and turbine inlet temperature capabilities will continue through 1980 (see figs. 94 to 97). This permits greater flexibility in selecting engine thermodynamic variables for application to a particular mission. Advantages that may result from these developments must be examined on an individual basis, since it is possible that some or all of these developments may not be required. An engine/aircraft matching analysis is necessary to ascertain the best combination of cycle parameters for a given mission.

Cruise Engine

The 1980 cruise engine can be expected to have the same diameter as its present counterpart. Little change is expected in hub-to-tip ratio, and since flow requirements fix the area required for any given mass flow, there can be little change in engine diameter for a given air flow.

Flow considerations would also prevent all but minor changes in inlet, burner, and nozzle lengths. However, the trend toward increased stage pressure ratios (see fig. 94) would permit a reduction in the number of compressor stages and hence in overall engine length.

Examination of a large number of turbojet and turbofan engines (ref. 3) has shown that state of the art advances can be expected to permit a 4% per year weight reduction. The weight of an engine may be expressed as

$$W_{t\ year} = W_{t\ 1970}\,(0.96)^{(year-1970)}$$

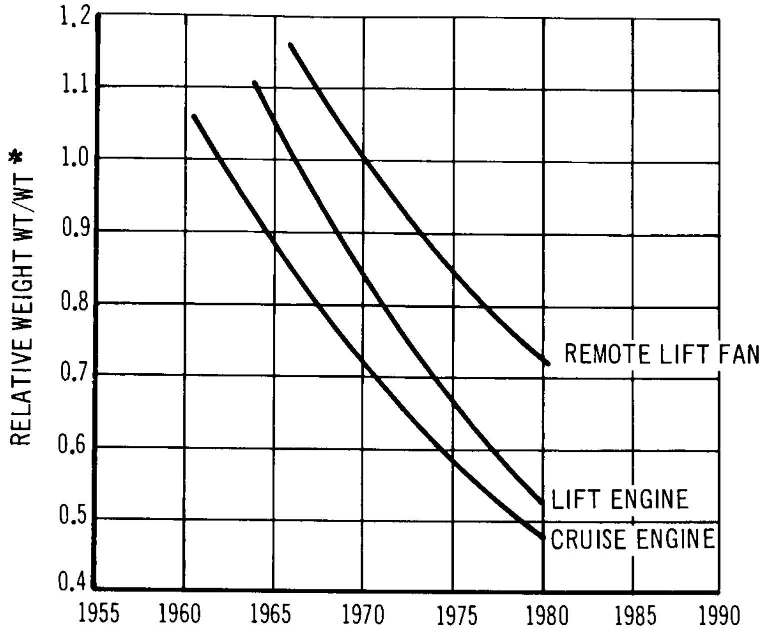


Figure 93: Expected Trend in Engine Weight

Lift Engine

It is assumed that by 1980 lift engines with dual spool compressors will have been developed. Because the stages of the compressor do not have to operate at the same speed, a higher stage loading can be used than in today's single spool compressor due to a better match. Because of this, a higher pressure ratio can be obtained than with today's engine; and for any given pressure ratio, a shorter compressor may be used. Based on extrapolation of statistical information, an engine thrust-to-weight ratio of 40:1 can be expected by 1980.

Remote Coupled Lift Fans

If the present level of development of remote coupled lift fans continues, it is assumed that a 10% reduction in weight compared to present technology levels can be achieved. New designs with higher stage pressures can be expected to reduce fan diameters 5% for a given pressure ratio. The combined effect of reduced diameter and weight results in a 28% fan weight decrease. Without an interconnect duct, the remote coupled fan plus its gas generator will approach a thrust-to-weight ratio of 20. However, if the first application of a remote coupled lift fan is not until 1980, it is very likely that only minor improvements in engine weight and performance will develop over today's levels.

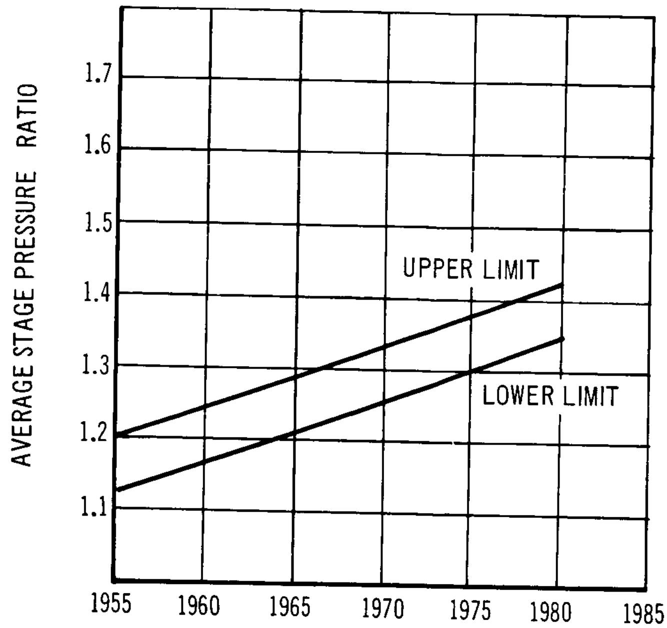


Figure 94: Average Stage Pressure Ratio Trend

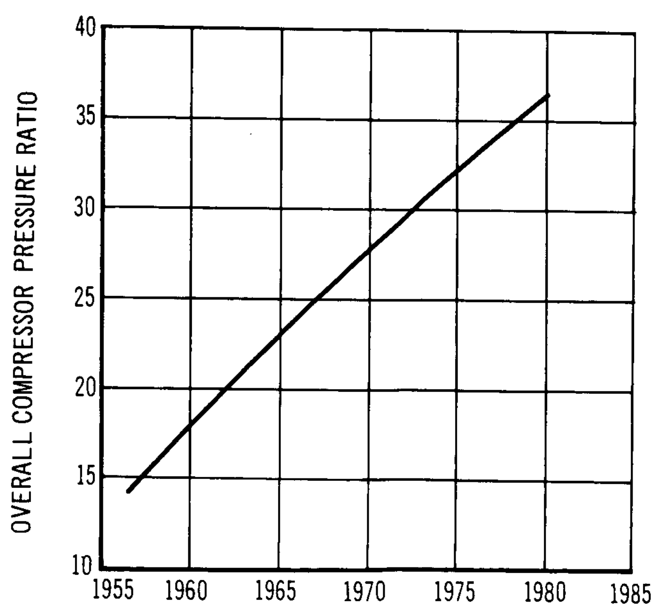


Figure 95: Trend of Maximum Engine Pressure Ratio

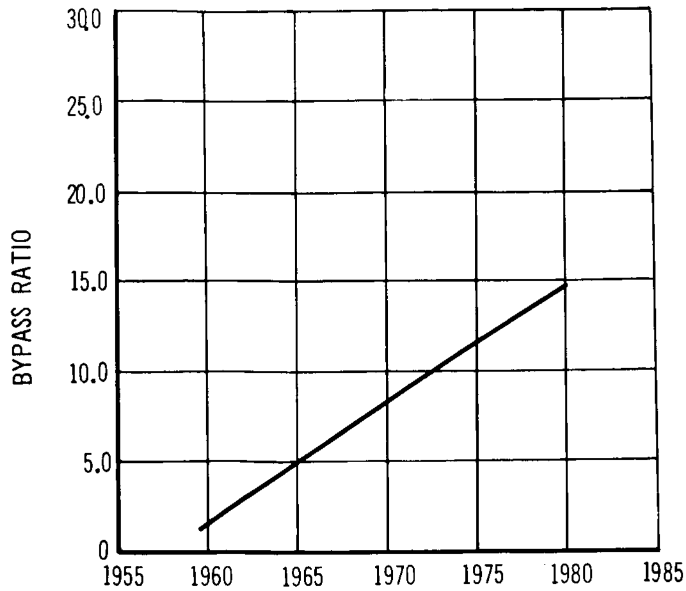


Figure 96: Trend of Maximum Bypass Ratio

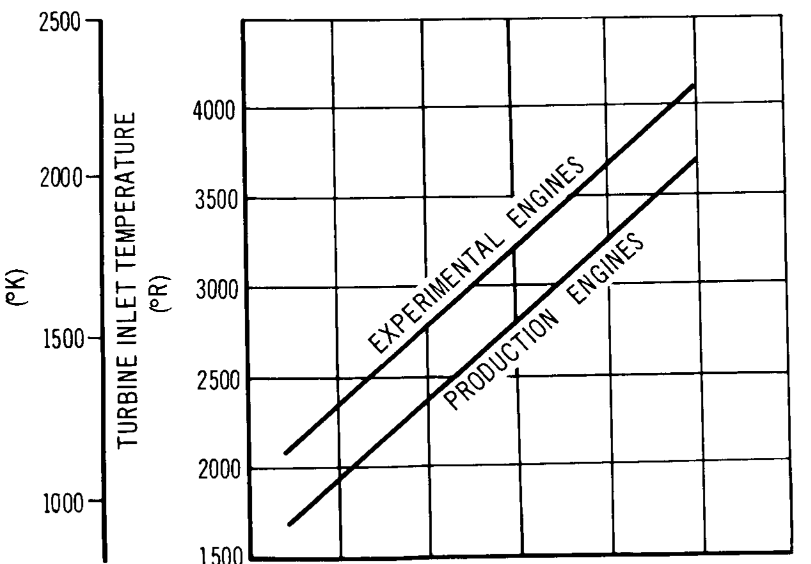


Figure 97: Turbine Inlet Temperature Trend

Gas Generator

The gas generator is a turbojet used to drive the remote coupled lift fan. For purposes of weight and size estimation, it may be assumed to be identical to a lift turbojet if a high thrust-to-weight ratio is desired. If, however, the gas generator is to be designed as a long endurance engine, the weight will be comparable to that of a cruise turbojet.

Engine Cycle Evaluation

Engine cycle selections for this study are based on aircraft gross weight. For a particular aircraft configuration and a particular mission, those engine cycle combinations that provide the lowest gross weight airplane are used, since it is considered that this will provide the least expensive system.

Cruise Engine Selection

Increasing the burner discharge temperature on a conventional air-breathing propulsion cycle is an accepted technique for increasing the thermal efficiency of the cycle. Considering cycles that have been optimized for bypass ratio and compression ratio, this means that an increase in T_4 will allow a reduction in mission fuel requirements. The time period for this study is 1980; turbine inlet temperatures of 3600°R (2000°K) and pressure ratios of 40 are therefore technically possible.

As an example of the parametric cycle analysis performed in this study, fig. 98 is presented. This cruise engine evaluation shows that aircraft gross weight to perform a given mission decreases as T_4 increases, but the amount of change is becoming less significant. As temperature increases, there is a requirement for higher bypass ratios to achieve minimum gross weight (see figs. 99 and 100).

This evalution also indicates that use of much higher turbine inlet temperatures of the order of 3600°R (2000°K), which would involve the use of cryogenic fuels, did not appear necessary. The further decrease in aircraft gross weight would be less than 0.5%. Increasing engine pressure ratios would also produce small gains because the aircraft weight is not affected by large cycle variation. For the engine cycles that were considered, the total variation in gross weight was less than 3%.

The insensitivity of the aircraft weight is a result of the short-range mission.

Convertible Cruise Fan Engine

In recent years interest has increased in convertible aircraft that combine the hovering characteristics of the helicopter and the high-speed cruise capability of the conventional turbofan or turbojet aircraft. A severe weight penalty results from the use of separate engines to drive rotors in hover and to provide cruise thrust. Therefore, various arrangements have been studied that allow common gas generators to fulfill both of these functions. These arrangements can be divided into two broad categories, gas-driven and shaft-driven,

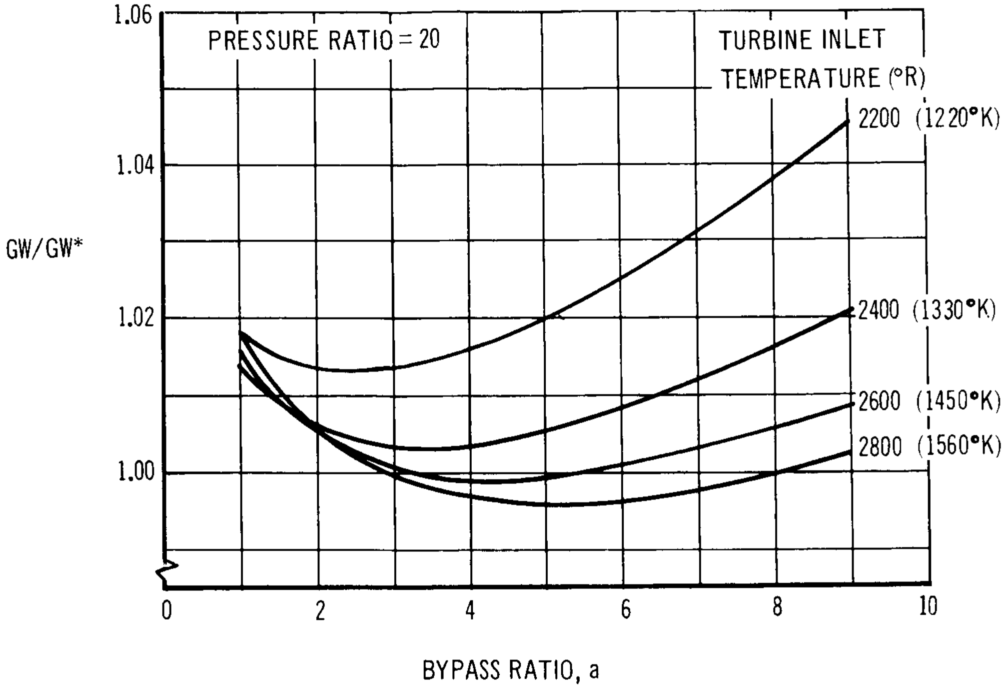


Figure 98: Cruise Engine Cycle Selection—CTOL

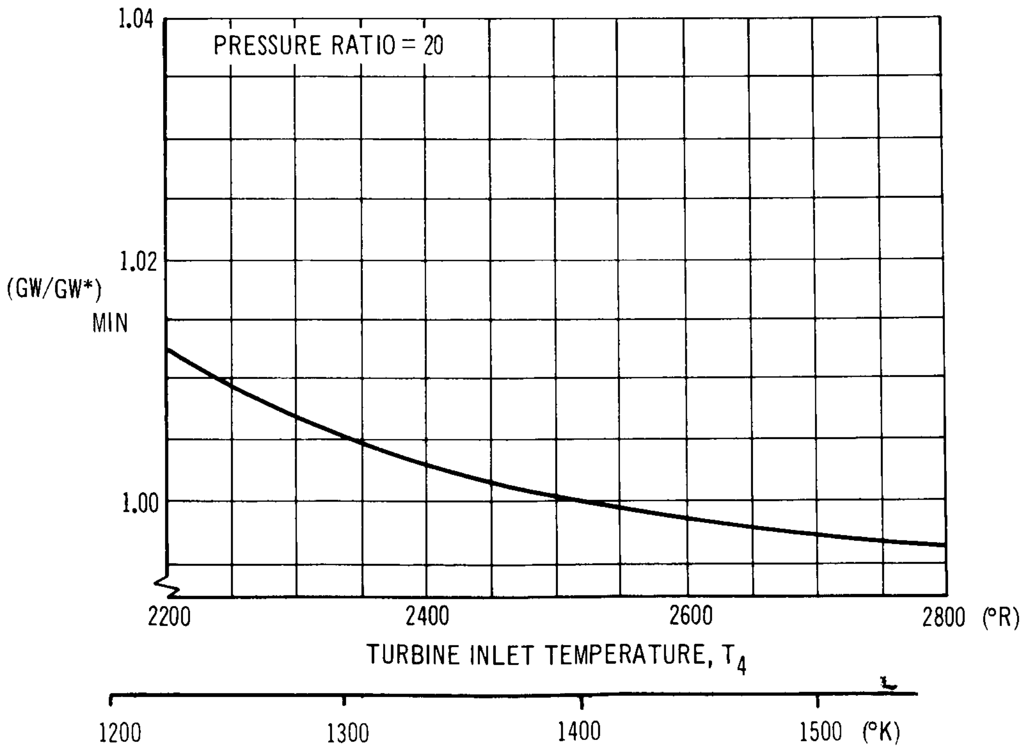


Figure 99: Effect of Design T_4 on Gross Weight—CTOL

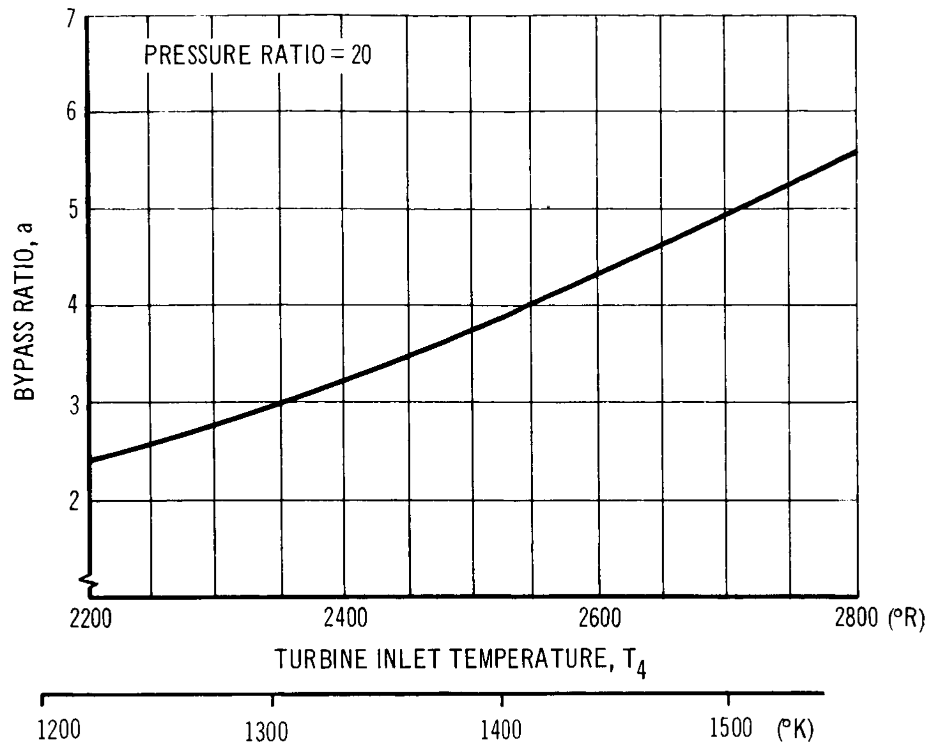


Figure 100: Effect of Design T_4 on Bypass Ratio—CTOL

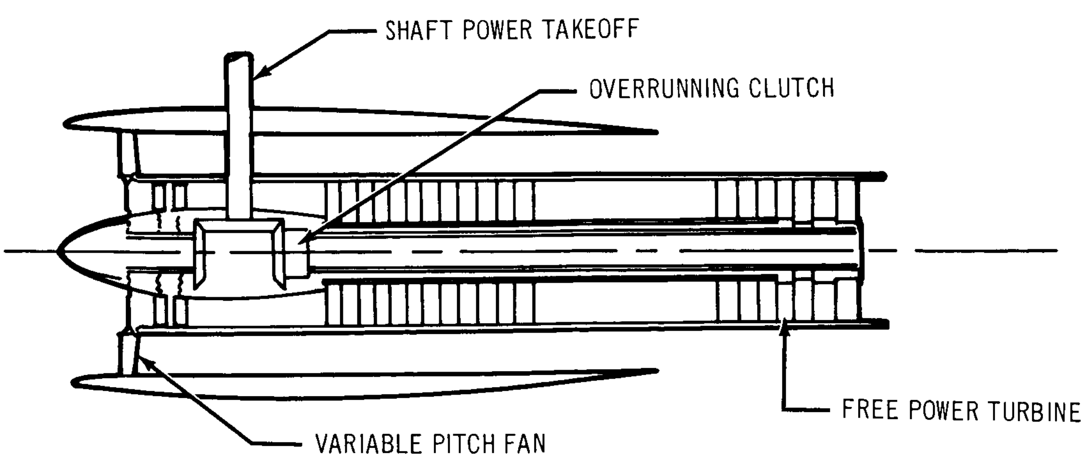


Figure 101: Schematic of Convertible Fan Engine

and in certain cases combinations of both. Reference 11 presents the results of a Boeing feasibility study of a broad spectrum of such systems as applied to future compound and composite aircraft. It is concluded that a shaft-driven system, utilizing convertible fan engines, is superior to any other, especially in the area of propulsion system/airframe design integration. This system is therefore adopted for the commercial short-haul study.

A schematic diagram of a convertible fan engine is shown in fig. 101. A gas generator drives a conventional free-power turbine, which in turn drives the power takeoff shaft through an overrunning clutch and bevel gearbox. The schematic shows a front drive power takeoff, but a rear drive can also be used. The overrunning clutch automatically disconnects the engine from the aircraft dynamic system in the event of a gas generator or power turbine failure. A variable pitch fan is driven from the front of the bevel box. The power turbine, fan, and aircraft dynamic system operate at a constant speed. The proportion of fan thrust and shaft power required is determined by the blade angle of the variable pitch fan and the load in the dynamic system that would be determined by the collective pitch setting of the rotor blades.

7.1.1.3 Noise analysis. — Exterior sound levels for each aircraft are predicted using conventional prediction techniques based upon propulsion system parameters. The conditions assumed for the calculations are:

- Sea level standard day, no wind, no reflections
- Cruise engines at maximum thrust during takeoff and 0.5 maximum thrust during approach except for the STOL high-lift engines at 0.75 maximum thrust on approach
- Lift engines at maximum thrust during liftoff throttled back to zero by end of transition. ("HIAC" STOL lift engines cut to 0.25 maximum thrust for 20° (0.35 rad) climb and off for 9.6° (0.17 rad) climb)
- Lift engines at 0.75 maximum thrust during approach

In calculating the exterior noise level environment, the directivity or noise radiation characteristics of each propulsion system is assumed to be symmetrical about the longitudinal axis. The direction of maximum sound radiation is considered to be similar to the directivity found in refs. 12 and 13.

To determine perceived noise level contours, the maximum perceived noise level at several distances was first determined as follows: the maximum levels were determined as a composite of jet noise, inlet noise, and fan discharge noise. The jet noise is determined as a function of exhaust velocity and also as specified in ref. 12. Using ref. 13, the inlet and fan discharge noise are determined as functions of engine rpm and inlet diameter. These levels are then extrapolated to various distances using ref. 14, and where appropriate, ref. 15. Standard procedures in ref. 16 are used to convert these noise levels to subjective perceived noise levels. Reference 17 provides conversion factors to obtain composite noise rating from perceived noise level.

The preceding levels, extrapolated to various distances, are also determined at numerous elevation angles relative to a particular sideline distance (see fig. 102). Consideration of the elevation angle determines the effect of ground interference on sound wave propagation. The extrapolated levels are plotted as a function of sideline distance and elevation angle. A crossplot of this information provides what has been called "contours in space" (see fig. 102).

With this plot and variations in the height of the ground plane, the reference levels can be traced on a flat, unobstructed ground plane as the aircraft executes its flight plan. These contours in space give the noise level on the ground with the aircraft at various altitudes, and also the level on nearby structures only with the aircraft on the ground. To determine levels on nearby structures while the aircraft is above or to the side of a building, new contours in space must be determined without regard to ground attenuation effects. The established noise contours for each concept and their relationship to city maps will be found in sec. 7.1.2.7.

Numerous evaluation techniques have been devised to determine the noisiness or annoyance of a particular sound as functions of one or more of the following: magnitude, frequency of occurrence, frequency content, and duration. It is presently impossible to conceive what the judgment criteria will be in 1985. In this report, perceived noise levels (PNL) are used as criteria. These are calculated from frequency spectra. Other criteria are community noise ratings (CNR). In addition to frequency spectra, these depend on occurrence frequency and can be obtained from the PNL (refs. 16 and 17).

The levels predicted for this program have included engine design changes such as no inlet guide vanes, increased rotor-stator spacing, lower tip speeds, and inlet treatment. Specifically, these changes are: 6 PNdB reduction due to removal of inlet guide vanes, 2 PNdB due to increasing rotor-stator spacing, 4 PNdB due to reduced fan tip speed, and 3 PNdB due to acoustical treatment of the inlet. For the rotor concepts a reduction of 10 PNdB is included to reflect the elimination of the blade bang phenomen.

It was found that changing the number of compressor blades from 40 to 50 resulted in 0.5 PNdB variation in engine noise. Figure 103 shows the changes in engine noise due to variation in engine design tip speed. Jet noise predominates at a bypass ratio less than 3. The effect of design tip speed is therefore small. At higher bypass ratios, the difference is 6 PNdB between 1200 and 1600 ft/sec (366 and 488 m/sec) design tip speed.

For remote coupled fans at very high bypass ratios, the tip speed is a function of fan pressure ratio. For an optimum engine cycle at a given bypass ratio, fan pressure ratio is a function of turbine inlet temperature. Figure 104 shows that the reduction in tip speed will eventually increase the noise because the fan area becomes very large to produce a given thrust.

Except for remote coupled lift fans, it is concluded that a compressor or fan tip of 1200 ft/sec (366 m/sec) and 40 blades will be used in parametric engine noise analysis studies.

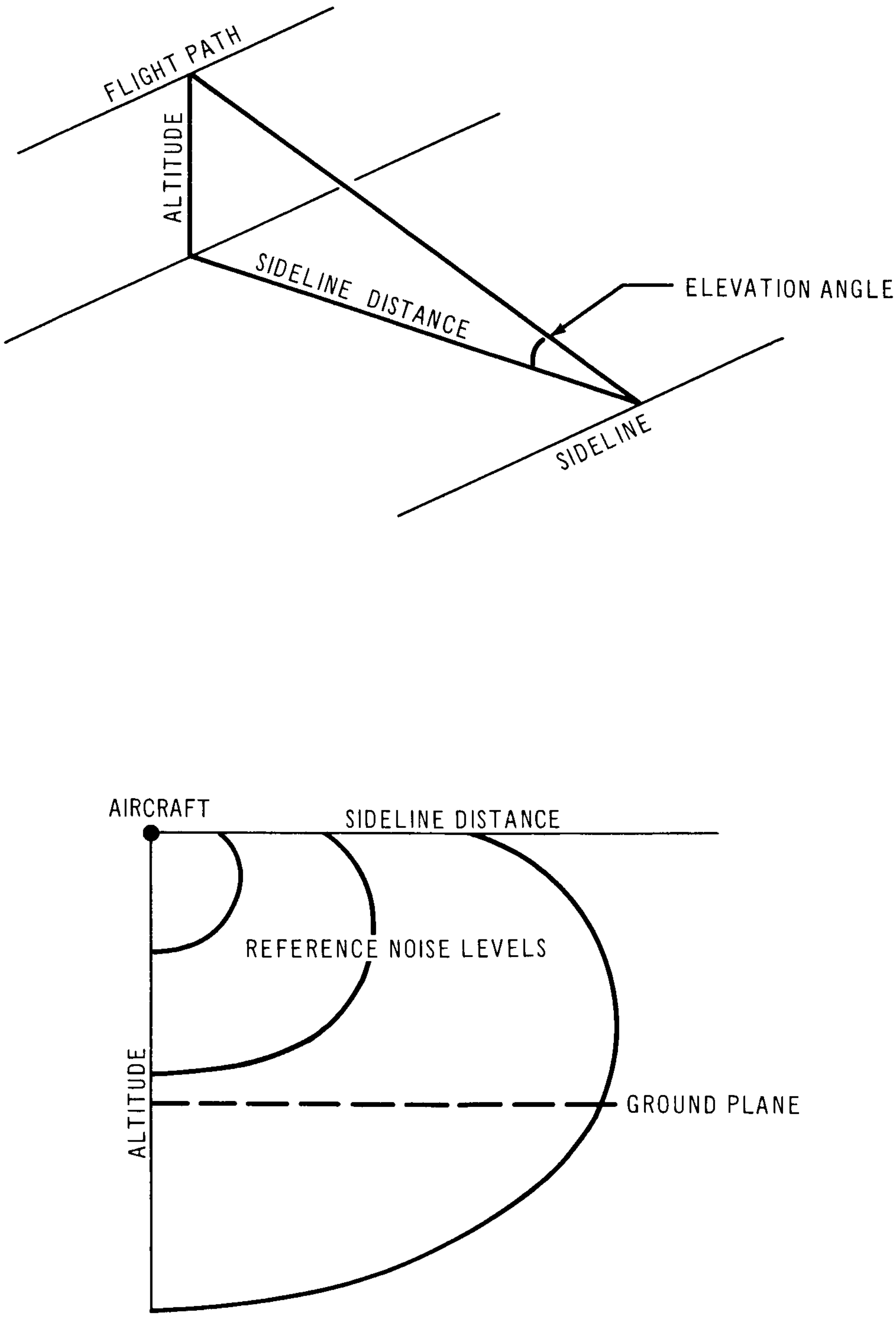


Figure 102: Ground Contour Determination

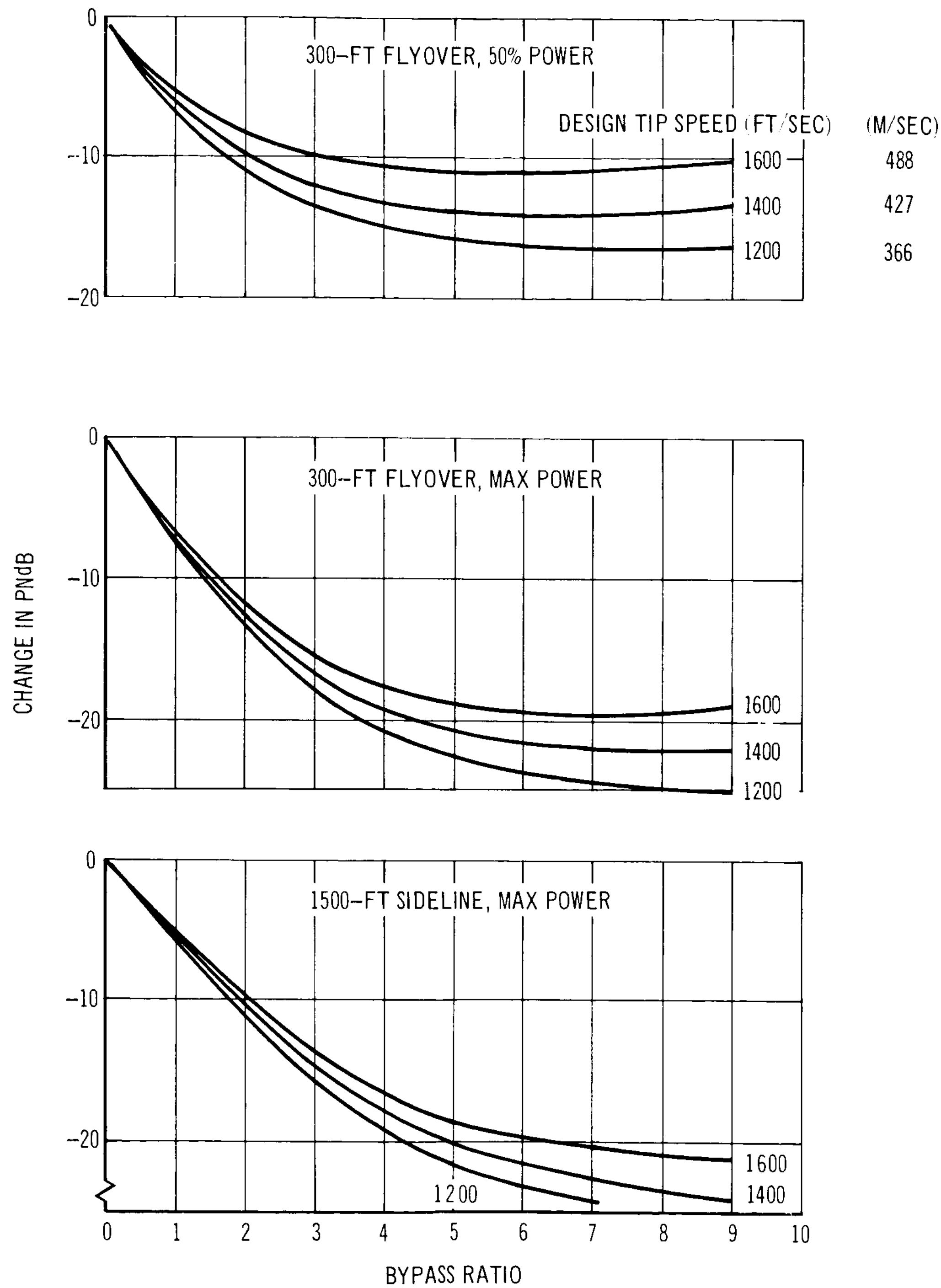


Figure 103: Engine Noise—Effect of Varying Design Tip Speed Turbofan and Turbojet Engine

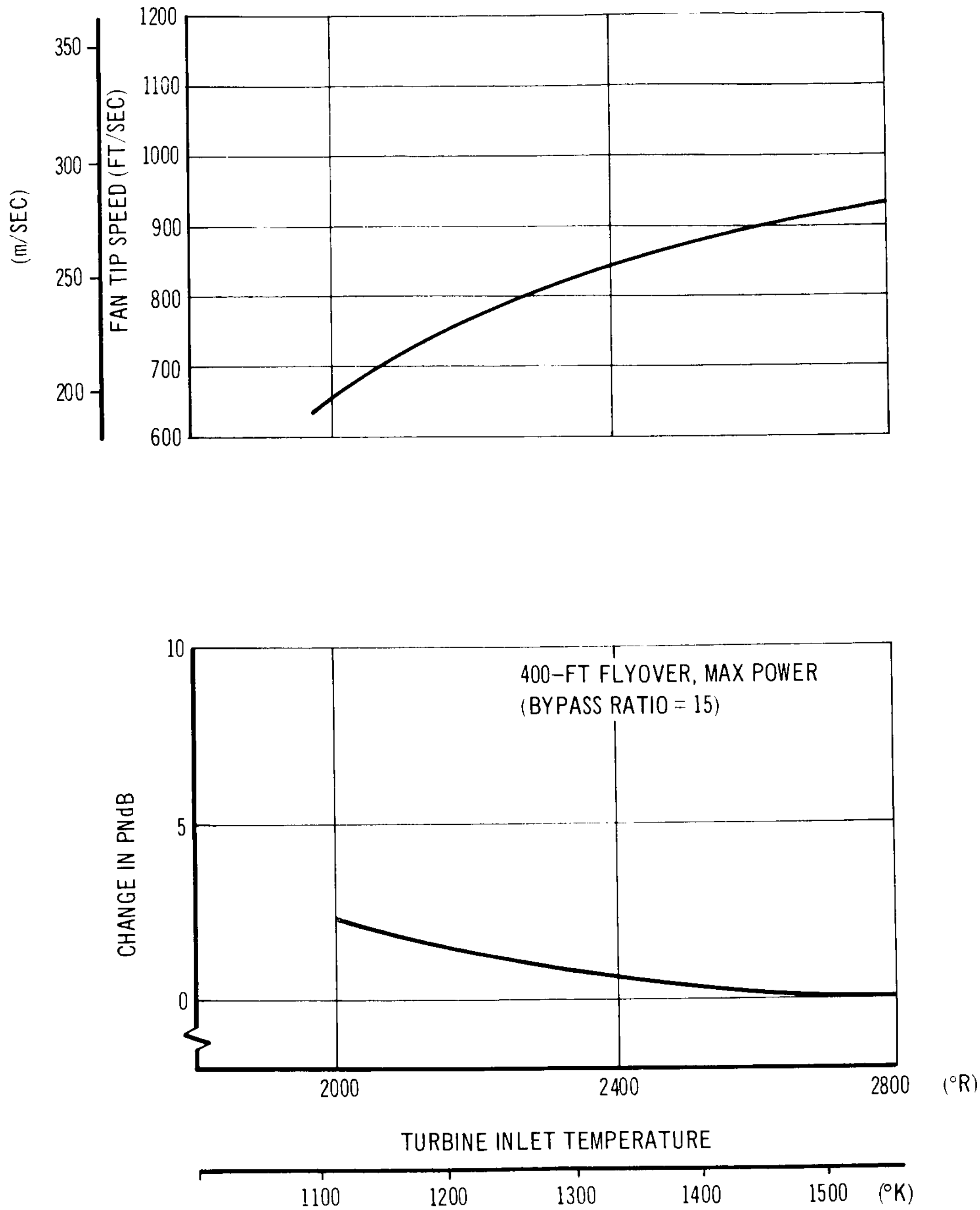


Figure 104: Engine Noise—Effect of Varying Design Tip Speed Remote Coupled Fan

7.1.1.4 Structures and weights analysis. —The following section summarizes the analyses performed to establish the structure and equipment weight levels to be expected in 1985 aircraft. A review of advanced structural materials is presented that leads to recommended reduction factors to apply to weight estimating techniques established for structures of current materials. In addition, a review is presented of equipment weight improvements expected by 1985.

A review of available and potential structural materials that could be used in 1985 is shown in fig. 105 on the basis of a simplified but important criterion, viz., strength-to-density ratio. This indicates that the reinforced plastic matrix composites appear to offer the most potential where strength is required at a minimum weight and where there are no environmental temperature problems to consider. Other factors must also be considered, e.g., stiffness properties, fatigue and crack propagation characteristics, producibility, formability, and material costs. However, considering the critical importance of minimum weight to V/STOL aircraft, the decision was made in this study to utilize filament-reinforced materials as the basic structural material. For comparison purposes, an estimate of an advanced titanium design is included.

Advanced Filament Composite Materials

A review of existing literature dealing with reinforced composite materials and their strengths was made (see refs. 18 through 32). To provide a preliminary working estimate of aircraft structure weight when manufactured from these materials, an analysis was made that is discussed briefly in the following sections.

Boron Filament/Epoxy Matrix Composites (1966)

Boron filament technology in 1966 appears to be at a very early stage of development, characterized by considerable scatter in test results, test methods, composite fabrication techniques, and matrix material choice. A number of companies and laboratories, including several Boeing organizations, have tested or are in the process of testing single boron filaments and small boron/epoxy composite specimens.

Allowable stress determinations for this study are based on the following general assumptions:

- Average single filament strength is used.
- A filament content of 65%, considered as good for hand layup technique, is assumed for a "rule of mixtures" strength ratio. This value is limited to a maximum of about 78% by the geometry of round filaments and also by resin strain considerations (ref. 28).

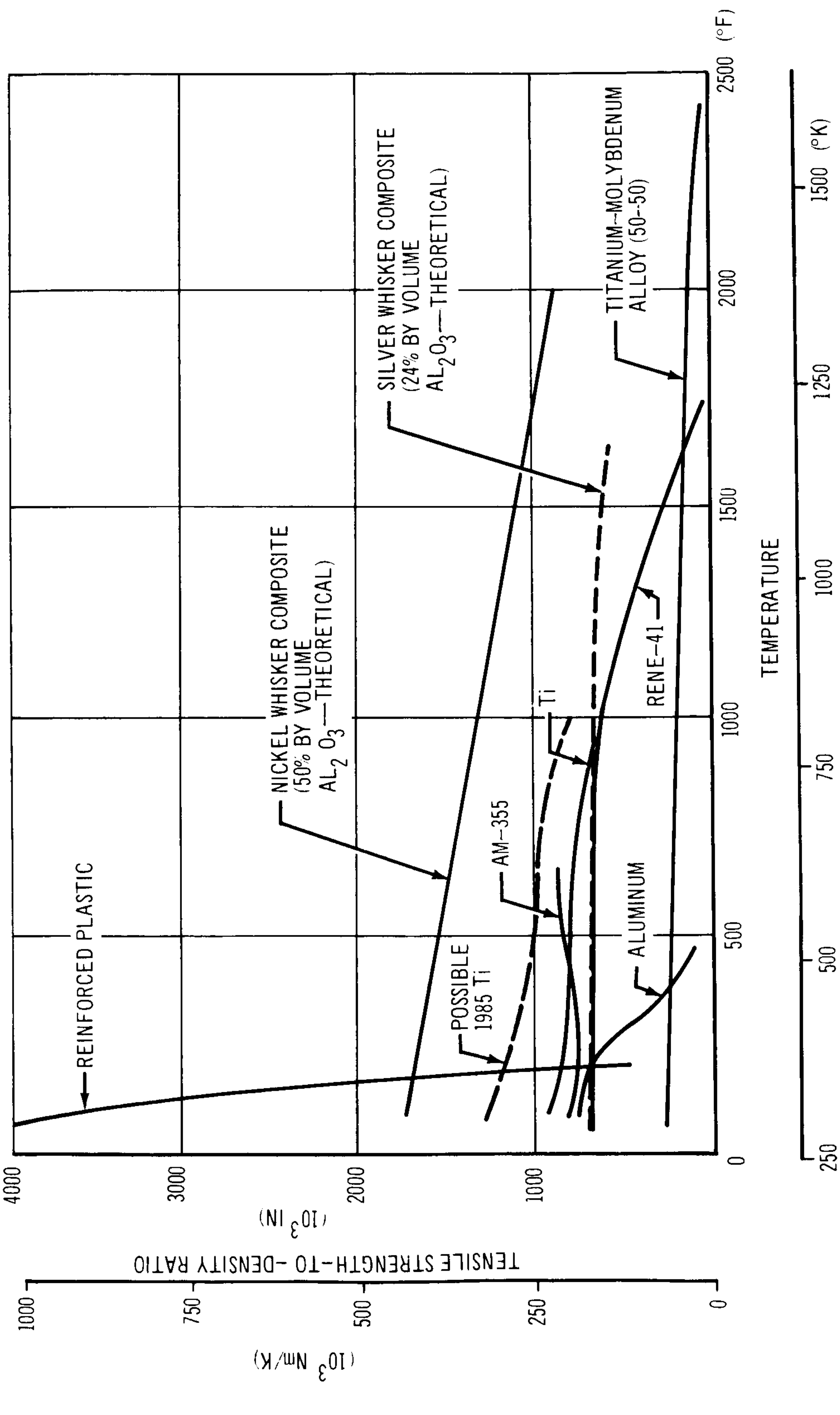


Figure 105: Material Strength-to-Density Ratio

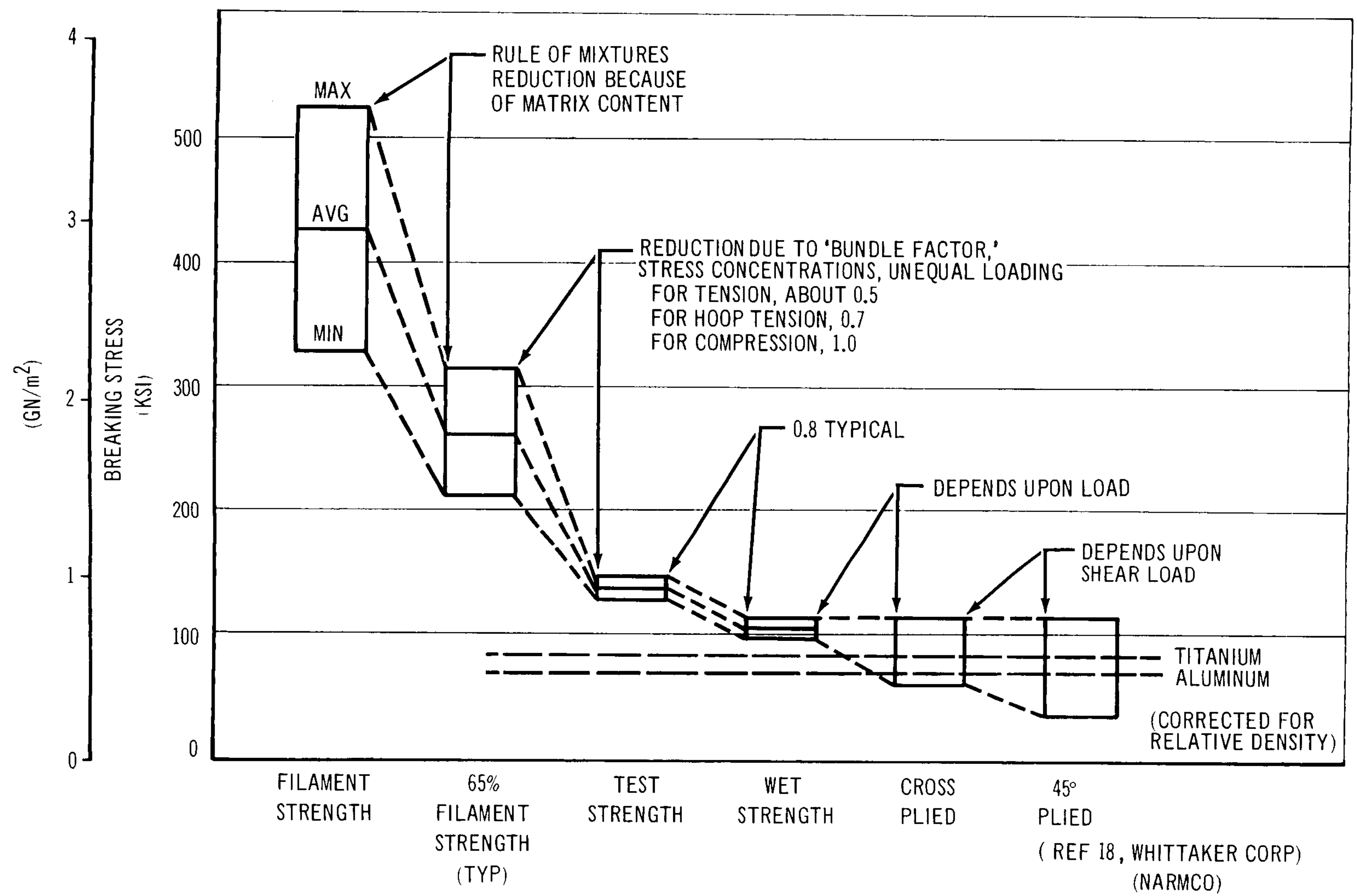


Figure 106: Typical Loss of Strength from Filament to Composite

- A filament efficiency factor is used to bring derived strength into agreement with average test results. This factor may be due to the Weibul "bundle factor" (ref. 28), unexplained stress concentrations, dynamic stress concentrations such as have been derived for filamentary materials (ref. 23), or some other as yet unknown reason. For direct tension, η = 0.50; for hoop or hydrostatic tension and flexure, η = 0.70; for compression, η = 1.0. η is defined as the composite test strength divided by the composite strength that would be predicted by the rule of mixtures and the average single filament tensile strength.
- A wet-strength requirement of 80% is used as the 1966 average for composites pretreated for high wet strength (ref. 26).
- The strength in other planes and other than unidirectional layup is assumed in agreement with refs. 24 and 31.

Most other composite properties can be predicted by a rule-of-mixtures calculation when the single filament and matrix properties are known (refs. 21 and 22). Predicted and experimental moduli of elasticity are in quite good agreement, and density is quite easily predicted. Typical single filament properties for boron are as follows for 1966:

Tensile strength	350 ksi average	(24.1×10^8 n/m^2)
Elastic modulus	60×10^6 psi	(41.4×10^{10} n/m^2)
Density	0.084 lb/in.^{3}	(2320 kg/m^3)
C_V (tensile strength coefficient variation)	0.20 typical	
Diameter	0.004 to 0.005 in.	(1.02×10^{-4} m to 1.27×10^{-4} m)

Material with a tensile strength of 400 ksi (27.6×10^8 n/m^2) is reportedly available. It is also reported that 0.001 in. (2.54×10^{-5} m) diameter filament, and filament with a 70×10^6 psi (48.4×10^{10} n/m^2) elastic modulus is available.

Boron Filament Composites (1985)

A number of improvements are possible and are considered likely in both single filament and composite properties by 1985. Smaller diameter filaments with better properties have already been reported. Better control of manufacturing processes should give more consistent filament strength with correspondingly improved composite performance. Improved matrix materials will reduce the penalty imposed by wet-strength considerations as well as improve the transfer of loads from one filament to another, which should improve filament efficiency within the composite. If the problem of residual stresses and radial cracking of tungsten core filament is solved, or another material is substituted for the core, the strength and quality of the filament should be improved and the cost reduced.

Figures 107 and 108 show the assumptions and postulated trends to predict 1985 properties. Reference material is indicated on the figures. Figure 109 shows for reference the assumed values together with predictions of other material strengths.

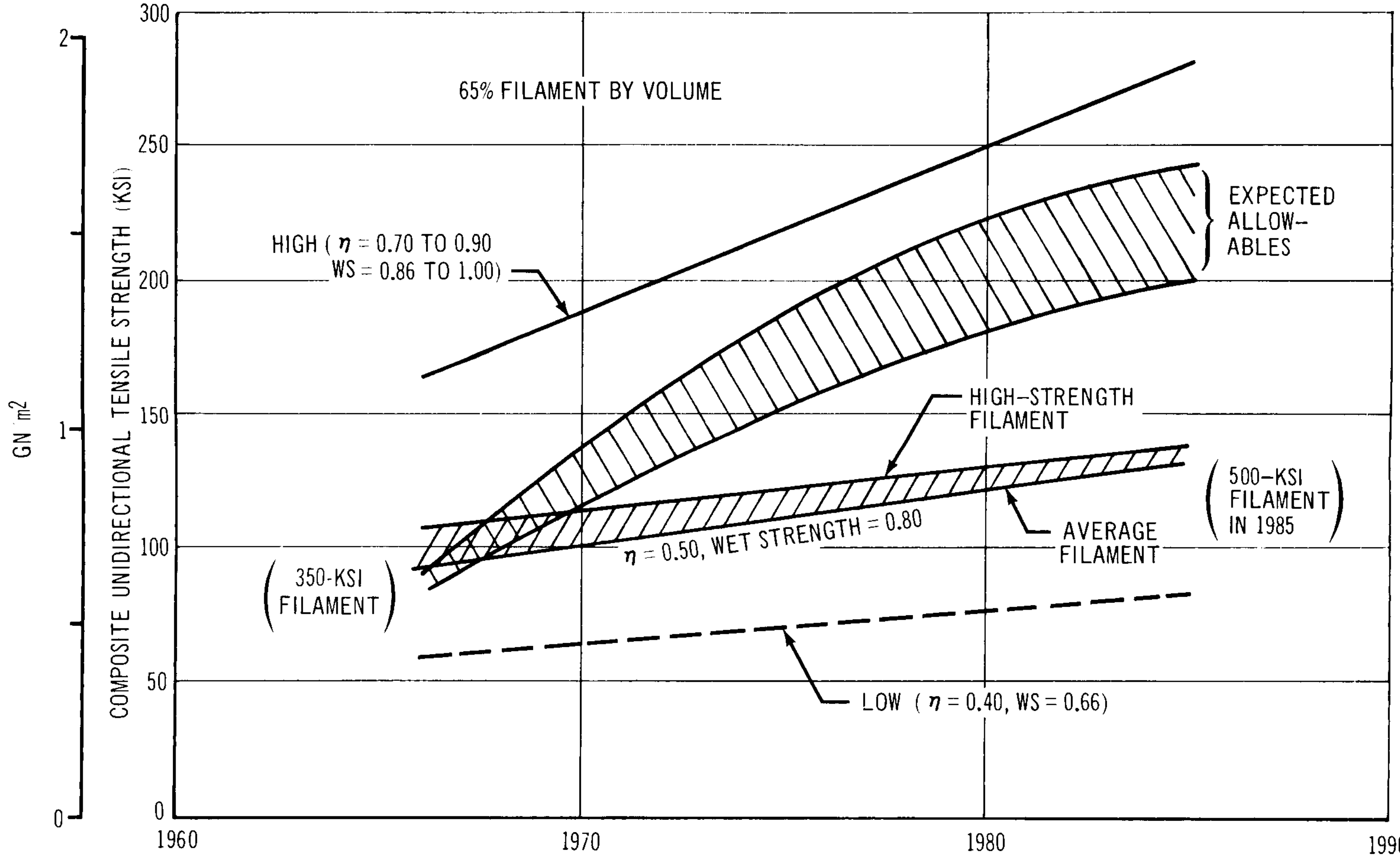


Figure 107: Reasonable Bounds for Boron Composite Improvement

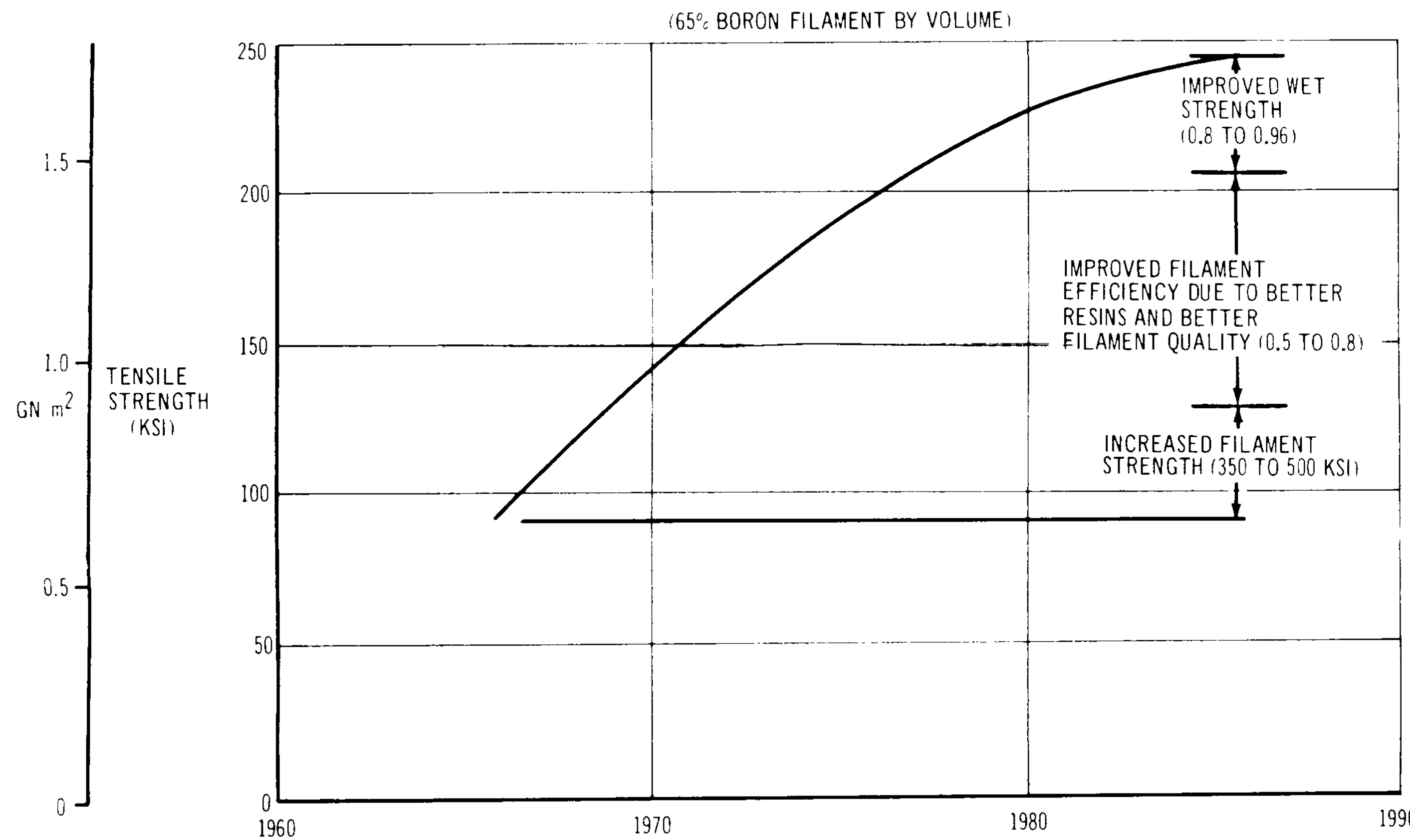


Figure 108: Expected Unidirectional Composite Tensile Strength

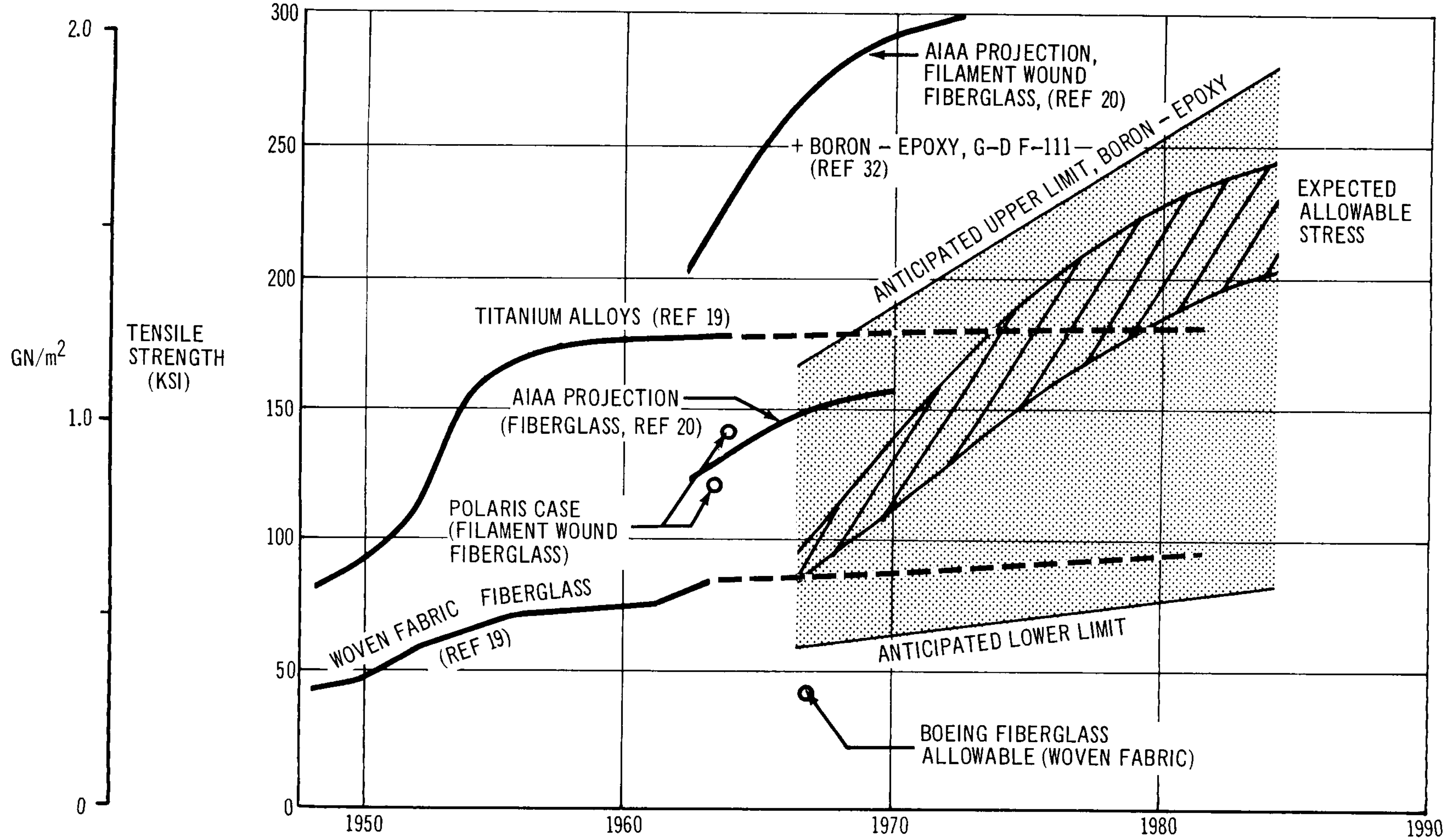


Figure 109: Comparison of Material Strengths

Typical single filament properties for boron are as follows for 1985:

Tensile strength	500 ksi average	(34.5×10^8 n/m^2)
Elastic modulus	60×10^6 psi	(41.4×10^{10} n/m^2)

Specific composite properties for 1985 weight calculation purposes are as follows:

Filament content by volume	65%	
Density	0.073 lb/in.^{3}	(2020 kg/m^3)
Unidirectional tensile strength	246 000 psi	(17.0×10^8 n/m^2)
Unidirectional elastic modulus	40×10^6 psi	(27.6×10^{10} n/m^2)
45° - 45° tensile strength	29 500 psi	(20.4×10^7 n/m^2)
45° - 45° shear strength	56 000 psi	(38.7×10^7 n/m^2)
45° - 45° elastic modulus	10×10^6 psi	(6.9×10^{10} n/m^2)
45° - 45° modulus of rigidity	10.8×10^6 psi	(7.46×10^{10} n/m^2)

Graphite Filament/Epoxy Matrix Composites (1985)

This is a composite with considerable promise for a number of reasons, a few of which are included as follows:

- Potential low cost, made from rayon or similar fiber in relatively simple process
- Small filament diameter allowing small radius bends and good "draping" for layups
- High strength, as high as, or higher than, boron
- High modulus, presently as high as 50×10^6 psi (34.5×10^{10} n/m^2) with potential to over 100×10^6 psi (69×10^{10} n/m^2)
- Heat-resistant capability
- Low weight
- Strength and modulus can be tailored to given application

The carbon filament modulus of elasticity is 75×10^6 psi (52.4×10^{10} n/m^2) by 1985. A carbon density of 0.054 lb/in.^{3} (1500 kg/m^3) is expected. Other rules for establishing working strengths are as for boron filament composites. Typical composite properties are as follows:

- 65% filament by volume
- Density 0.0525 lb/in.^{3} (1450 kg/m^3)
- Unidirectional tensile strength 246 000 psi (17.0×10^8 n/m^2)
- Unidirectional modulus 49×10^6 psi (33.8×10^{10} n/m^2)

General Considerations — Boron/Epoxy Composites

A weight increment for rain and erosion protection is required for exposed fiberglass parts by Boeing. It is considered likely that it will be required for boron and graphite/epoxy composites.

Joints, attachments, access panels, and discontinuities make exact weight analysis exceedingly difficult without detail design. While the weight penalty is unfortunate, it is unlikely that any large structural component for a commercial aircraft would be designed without these necessities because of ease of maintenance, damage repair, individual customer requirements, refinement of design while in production, and convenience in production.

Fatigue data on boron and graphite filament epoxy matrix composites are quite limited and demonstrate considerable scatter. For this study, the following assumption is made: It is recognized that much research and development will be applied to this subject by 1980; thus it is assumed that where aluminum has an acceptable fatigue life at a given stress level, a boron or graphite filament-reinforced epoxy composite will have a similar fatigue life at a stress level higher by the ratio of the ultimate strength of the two materials. This assumes that research will generate a trend, similar to that of aluminum, of fatigue life versus stress level for the filament-reinforced epoxy composites.

Metal Matrix Composites (1985)

Use of a metal matrix such as aluminum or titanium would result in a heavier composite than the organic matrix composites, but the material might allow use of conventional joining and fabrication methods and perhaps result in a more satisfactory structure from the standpoint of manufacture, repair, maintenance, inspection, and modification.

Typical areas of application could be:

- As a higher strength/density replacement for the high-strength steels in use in such areas as the landing gear
- In the manufacture of smaller and lighter fittings, end caps, etc., that are now made of aluminum
- As an intermediate or transition material in joints between metal and plastic composites to relieve the strain incompatibility of the two

A number of different metal composites are possible, but the following are considered as the most likely for future use in subsonic aircraft:

- Carbon filament/titanium matrix
- Carbon filament/aluminum matrix
- Carbon filament/magnesium matrix
- Boron filament/aluminum matrix
- Boron filament/magnesium matrix

Boron and carbon are considered as the two most likely filament materials because of the effort that has been expended in their development and the possibility of reasonable material costs.

As an example of the application of some of these materials, a typical landing gear was analyzed.

The best hypothetical composite of those reviewed is carbon filaments in a magnesium matrix, which gives 18% saving in weight. Titanium appears least attractive as a matrix material, probably because of its weight, while carbon shows an advantage over boron as a filament, again because of weight.

Estimation of Airframe Component Weights Using Composite Materials

Boron Filament/Epoxy Matrix Composites — The following methods are used to derive simple reduction factors that could be applied to weight estimates of conventional aluminum alloy structures. These factors will reflect the substitutions of some of the aluminum material by boron filament/epoxy composites where the properties of the composite are as shown earlier.

Shear Material — When shear strength and not rigidity is the criterion, the relative weight of a composite component is assumed equal to the weight of the aluminum component times the ratio of the shear strength of the materials times the ratio of the densities.

If resistance to buckling in shear is the design criterion, a different calculation involving the elastic moduli is used (ref. 24).

Compression Material — Most compression material is used in such a manner that stability or structural index is the criterion rather than ultimate compressive strength. Critical buckling stress varies with the type of construction, but the formula is usually of the form $F_{ccr} = KE\,(t/a)^2$, where K is a constant for the particular case and t is the material thickness. The value of E refers to the single value for homogeneous materials, or more properly, the tangent modulus of these materials. Reference 24 recommends for laminates and anisotropic materials to replace E with E_aE_b, where E_a and E_b are calculated from the relationship

$$E_x = \frac{1}{I} \sum_{i=1}^{i=n} E_i I_i \qquad \text{about the axes } \Phi = 0 \text{ and } \Phi = 90^\circ.$$

Further analysis of compression structures utilizing honeycomb stabilized unidirectional material is not considered at this time.

Tension Material — Tension material can be replaced with unidirectional composite if stability under reversed loading is not critical. A simple strength-to-density relationship then exists.

Torsion Considerations — Since unidirectional filament composite is by far the strongest in tension or compression, it is desirable to use this form as much as possible for maximum weight reduction. One of the limitations of this form of composite is its inability to carry shear forces, making a 45° - 45° filament layup necessary in high shear areas.

It is assumed necessary to maintain the torsional rigidity of the wing, for instance, to at least the same level as that found in the aluminum wing. The material considered for spar webs (shear material) and the upper surface of the wing (compression material) will carry shear; to complete the torsion box, some shear material must therefore be placed in the wing lower surface. If half of the bending material of the aluminum wing is assumed to be in the lower surface and contributing to the torsional rigidity, then the torsional requirement is the aluminum weight in the lower surface times the shear modulus of aluminum, and the weight of composite shear carrying material is that product divided by the shear modulus of the composite and multiplied by the ratio of material densities.

Summary — Boron Filament/Epoxy Matrix Composites

Using the material properties developed for boron filament/epoxy composites and the weight analysis method and assumptions, the following reduced structural weights are predicted for a 1985 aircraft:

- Fuselage: 78.5% of aluminum fuselage weight
- Wing: 76% of aluminum wing weight
- Empennage: similar to wing

The reference aluminum weight is based upon 1966 aluminum allowables and properties.

Summary — Graphite Filament/Epoxy Matrix Composites

With the material properties shown earlier and the weight analysis methods as derived, the following reduced structural weights are predicted for a 1985 airplane:

- Fuselage: 69% of aluminum fuselage weight
- Wing: 64.5% of aluminum wing weight
- Empennage: similar to wing

It can be seen that this is approximately a 10% improvement over a boron filament/epoxy matrix composite structure.

Summary — Advanced Filament Composite Materials (Airframe Components)

The review carried out for this study indicates the following weight savings possible in airframe structures when various new materials are used:

	Percent of weight saving possible relative to a 1966 aluminum structure
Boron filament/epoxy matrix composite	22 to 24
Graphite filament/epoxy matrix composite	31 to 36
Graphite filament/magnesium matrix composite	18
For reference:	
An advanced titanium design	15 to 20

The aircraft configurations shown in this final report incorporate the expected weight savings using graphite filament/epoxy matrix composites.

Advanced Materials —Rotors, Gearboxes, Transmissions

Substantial savings in the weight of rotor blades and gearboxes will be realized in future years from state-of-the-art advances in materials, lubricants, and metallurgical techniques.

The use of single-crystal structure and improved lubricants will allow higher induced stresses in gearing, which in turn will result in a reduction in material and weight with an increase in service life (see fig. 110)

Rotor blade weight will be significantly reduced by using advanced filament composite materials such as boron in place of metal and fiberglass construction currently in use. Table 5 compares the current CH-47 blade weights with a boron-constructed blade. This indicates a savings in blade weight of 32 percent. Blades constitute approximately 60 percent of total rotor or propeller weight. Therefore, together with a weight saving of 19 percent with titanium used for hub components, a net savings of 25 percent on rotor and propeller weights is anticipated.

Predicted Equipment Weight Reductions

Instruments and Navigation —Instruments and navigation equipment may show a trend towards more displays. Integrated systems checkout will increase reliability. Miniaturization and solid state systems will, however, offset the probable weight penalties of the above improvements. Overall saving in weight is estimated at 20 percent.

Flight Controls —Here again there will probably be an increase in requirement and capability, but the improvements in structural materials and electronics will provide a 10 percent weight reduction.

Hydraulics —Improvement here expected to come from conversion to titanium tubing, use of new materials in jacks, valves, etc., and an increase in system pressure. A projected weight saving of 25 percent has been estimated.

Electrical — The power generation system could experience weight reductions of 25 percent due to combining constant-speed drive and generator functions in one piece of equipment. Increased rpm and new materials could allow weight reductions in motors and generators. Miniaturization of relays, switches, and breakers, increased system voltage, and use of solid-state switching could allow a 25 percent reduction in basic equipment weight. An estimated 30 percent reduction is expected in the area of wiring and connectors due to smaller diameter, higher-strength wire, lighter insulation materials, use of aluminum as feeder wire, and miniaturization of connectors.

Electronics —Weight reductions in this area are similar to the electrical systems. The trend in the last 7 years indicates a saving by 1985 of 35 percent.

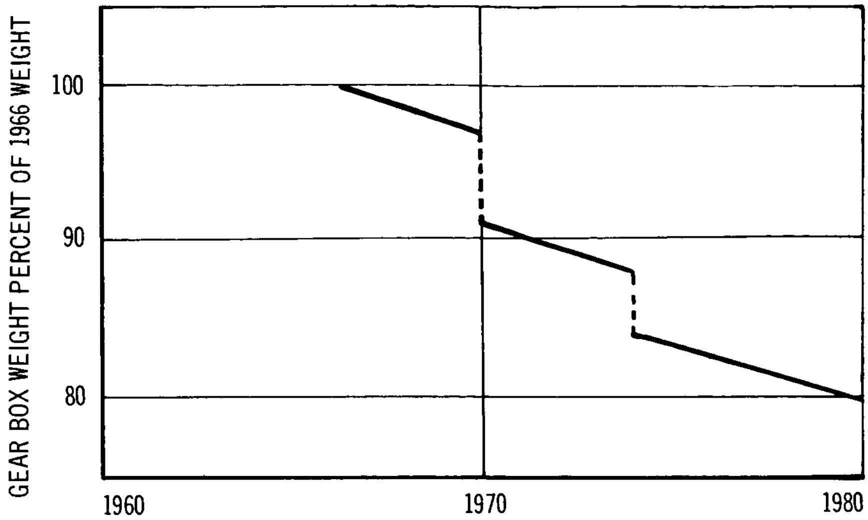


Figure 110: Expected Gear Box Weight Trend

Table 5: Typical Weight Breakdown

Components	Weight per blade (lb) Current CH-47	Boron CH-47
Spar	140.0	61.7
Leading edge	40.0	40.0
Trailing edge	5.7	3.0
Skin and ribs	25.8	25.8
Balance and tracking weights	15.1	11.1
Root end	31.0	31.0
Joints, splices, and miscellaneous	10.5	10.5
Total weight per blade	268.1	183.1
Total weight per aircraft	1608.6	1098.6

NOTE: lb x 0.454 = kg

Furnishings, Air Conditioning, and Anti-icing — A combination of improved seat design and new materials for structure and electrical systems will provide 20 and 10 percent weight reductions respectively.

Auxiliary Power Unit — Although demands on this unit will probably increase, gas generator technology of 1980 will be incorporated to provide an estimated 15 percent saving in weight.

7.1.1.5 Flight operations analysis. — Advanced technology determination in this area will be reviewed as follows:

- An examination of the landing aids, navigation aids, approach and takeoff profiles, ground terminal layout, and flight controls
- A description of the avionics equipment required for the various aircraft types, including communications, navigation, and landing equipment for STOL, VTOL, and CTOL
- A description of the 1985 air traffic control system and procedures, and an analysis of the possible track conflicts that could result from the introduction of the short-haul transport system in the 1985 traffic environment

Landing Aids

Several available systems will be studied and the factors affecting landing approach profiles and their interaction with other aspects of the landing problem will be discussed.

Ideally, the V/STOL landing system should have the following characteristics:

- Ground maneuver capability
- Adjacent location of landing sites for high traffic density
- At-will variation of approach profiles
- At-will variation of localizer approach angle
- Fully automated all-weather capability

Possible Systems

The conventional ILS system in use at the world's major airports provides a fixed path in space that can be followed down to varying heights above the runway as defined by the FAA/ICAO classifications detailed in Table 6. Most ILS systems provide Category I guidance, and a few systems are being updated to Category II standards. To proceed below Category I or II limits, further data need to be obtained by radio altimeter and glide path extension techniques. The ILS has many disadvantages. Among these is that an adjacent ILS beam must operate at a different broadcast carrier frequency and the frequency separation required limits the total number of ILS system in any particular area. After touchdown the ILS provides information only during rollout down to the runway end. Thus the ILS system does not meet any of the requirements of the ideal system.

Table 6: FAA/ICAO Classification of Weather Minimums

Operation	Propeller RVR* ft (m)	Propeller Ceiling ft (m)	Jet RVR ft (m)	Jet Ceiling ft (m)
Category I	2600(800)	200(60)	4000(1200)	300(90)
Category II	1300(400)	100(30)	1200(370)	100(30)
Category III-a	700(210)	50(15)	700(210)	50(15)
Category III-b	150(50)	0	150(50)	0
Category III-c	0	0	0	0

* Runway Visual Range

The FAA has sponsored the development of a family of pulsed scanning beam systems (REGAL, Flarescan, AILS) that erect a grid of angle and range information in the approach area out to 25 nautical miles (46 km). These allow the aircraft to locate itself in space relative to the ground plane of the runway and obtain guidance during approach, flare, and rollout down the runway. These systems would allow a VTOL aircraft to choose its own approach or takeoff profile (within limits), but adequate system separation is required because of beam dimensions and carrier frequency separation specifications. The systems do not allow controlled ground maneuvering.

Honeywell has produced a relatively inexpensive, portable, lightweight, pulsed lobe C band (5.1 GHz) radar (STATE), which provides a fixed path in space plus range information; but by pulse-coding techniques allows up to 25 ground stations to operate adjacent to one another at the same carrier frequency. If the system is inexpensive enough, the approach glide path angle or localizer angle could be varied by using a number of antennas positioned at the same site but which could be switched on and off at will. The system does not provide any controlled ground maneuver capability. Other portable systems exist, such as TALAR, and provide ILS type service but at higher carrier frequency to reduce side lobe effects and antenna size.

An alternate type of landing system uses precision distance-measuring equipment (DME) to show the location of the aircraft in space relative to the landing site. The rectangular coordinates x, y, z are calculated from measurement of the three slant ranges to the transponders. The transponders are arranged in a known geometrical pattern on the ground and reply to interrogation from the aircraft. If it were possible to establish accurate altitude data, any desired profile could be flown to the landing site. As a resulte of the geometry of the arrangement and the probable low approach angles (less than

10° or 0.175 rad), the determination of altitude by this means is not sufficiently accurate. Barometric altitude does not have sufficient absolute accuracy for operations close to the ground. The radar altimeter is very accurate but is noisy because it measures the terrain profile. Filtering is considered to be inadequate when operating over the unusually rough terrain typical of the city. Unless some technical breakthrough occurs, it does not appear likely that direct accurate determination of altitude without ground-based equipment will be possible in 1985 without a great deal of research. A ground-based, fixed-beam generator can be utilized to solve the altitude problem since it can provide a linear glide path to pass through a point vertically above the landing site. The transition would then be carried out on the fixed-slope glide path with a rounding of the trajectory to descent off the beam onto the landing pad using radar altimeter data. (Radar altitude can be used over the smooth surface of the landing site.) Clearly this is a definite operating restriction. It might be argued that a curved path is superior from several points of view. However, a strong case for a curved trajectory against a linear trajectory cannot be established. It is not practical to determine position away from the beam boresight because signal strength varies markedly with atmospheric and weather conditions. It would be possible to provide a dual or triple slope beam to simulate a curved path by doubling or tripling the number of beam generators to provide better obstruction clearance, but the maximum flightpath angle is limited by several factors. Using the coded fixed microwave beam (FMB) equipment, the changeover from one beam to the next would require a signal code change but not a frequency change. However, any kind of switching should be avoided in an autoland system. The azimuth coverage of the beam could be made wide enough to allow approaches from all directions by the use of several beam transmitters. Thus it would be possible to provide a system with fixed elevation guidance and all-azimuth approach capability. The DME equipment would provide localizer information and would continue to provide guidance on the ground. Use of the transponders would allow control of ground maneuvers from precise knowledge of the aircraft's position relative to the transponders and the layout of the transponders relative to the ground installations. By simple coding of the transponder interrogation signals and by the possible addition of extra transponders, a number of aircraft could be landed in the same area, their spacing depending on factors other than landing system interference effects.

If the all-azimuth capability can be sacrificed and a much smaller segment of operation is considered, the AILS type of system could be used to provide both elevation and azimuth coordinate information. As stated before, any type of curved profile could be followed with this system, but an azimuth restriction (for present equipment, ±24°, or 0.42 rad) is introduced. Unless the transmitter is placed far enough from the landing site to allow the beam envelope to cover the whole area, and if there are obstructions (buildings) to block the line of sight, then ground maneuver guidance capability will also be lost. Several segments of azimuth guidance could be obtained by placing several transmitters at the landing site, but they would have to operate at different carrier frequencies. This would limit the number of landing sites within a particular area. The present high cost of the AILS system also makes this solution very expensive.

Current Status of Systems

At the present time, only the ILS system is in regular use throughout the world. Only one complete unit of the advanced pulse-beam scanning system (AILS) has yet been produced and it is now undergoing FAA tests. If the system meets its specification, some time may elapse before it comes into general use at CTOL airports. Other systems, e.g. cheaper forms of the ILS or the STATE system, may well achieve a higher production volume in providing for installations at the smaller airfields used by feeder airlines and private flyers who will not require full Category IIIc blind landing facilities. The spread of electronic landing aids to small airfields will occur with the introduction of lightweight, inexpensive, reliable equipment. By 1985 considerable experience should have been obtained in using these systems. A VTOL landing aid system utilizing DME has not been tested in flight, but the techniques of precision distance measurement have been proved in several applications such as the SHIRAN system and the NASA Ames studies using an airborne DME system by Cubic. By 1985, the DME system should have had a long period of use and should be ready for utilization in the civil short-haul transport field.

Postulated 1985 System

The major features of available landing aids for V/STOL aircraft are presented in fig. 111. As mentioned earlier, the V/STOL landing system should have the following characteristics:

- Ground maneuver capability
- Adjacent location of landing sites for high traffic density
- At-will variation of approach profiles
- At-will variation of localizer approach angle
- Fully automated all-weather capability

A possible landing aid system for 1985 would probably be one of the two alternatives shown in fig. 112. The decision as to which one would involve study beyond the scope of this contract. The system A (DME plus FMB) costs more than system B, implies a duplication of some hardware, and requires a fixed and linear elevation approach profile. The system B (all-FMB, e.g. STATE) also requires a fixed and linear elevation approach profile, provides no ground maneuver capability, and is limited in the number of azimuth approach directions available by the number of transmitters used.

Navigation Aids

Economical short-haul transport system operation requires a navigation system that allows for point-to-point flightpaths. No special problems are predicted in this area. Several operational systems exist today that can satisfy the 1985 short-haul navigation requirements. These include VOR, TACAN, PVOR, DECCA, LORAN D, and Omega.

SYSTEM	ELEVATION TRAJECTORY SHAPE	ALL AZIMUTH APPROACH	ACCURACY	COST AND COMPLEXITY	GROUND MANEUVER GUIDANCE	NUMBER OF SYSTEMS IN AREA	PROBABILITY OF USE
1 DISTANCE MEASURING EQUIPMENT (DME) AZIMUTH GUIDANCE DISTANCE MEASURED	-	YES	GOOD	MODERATE	YES	ONLY LIMITED BY CODES AVAILABLE	POSSIBLE
ELEVATION GUIDANCE FROM a) CALCULATED ALTITUDE	CURVED OR LINEAR	-	UNUSEABLE	MODERATE	-	AS 1	VERY LOW
b) BAROMETRIC ALTITUDE	CURVED OR LINEAR	-	POOR	MODERATE	-	AS 1	LOW
c) RADAR ALTITUDE	CURVED OR LINEAR	-	UNUSEABLE (TERRAIN FOLLOWS)	MODERATE	-	AS 1	NONE
d) GROUND BASED BEAM (STATE)	LINEAR EXCEPT FOR FLARE INTO VERTICAL DESCENT	-	GOOD	MODERATE	-	25	POSSIBLE
2 MULTIPLE STATE EQUIPMENT. AZIMUTH AND ELEVATION GUIDANCE FROM SEVERAL STATE TRANSMITTERS	LINEAR EXCEPT FOR FLARE INTO VERTICAL DESCENT	NUMBER OF APPROACH DIRECTIONS LIMITED BY NUMBERS OF TRANSMITTERS	GOOD	LOWER THAN DME COMBINATIONS	NONE	25 DIVIDED BY NUMBER OF TRANSMITTERS	POSSIBLE
3 SCANNING SYSTEMS (AILS) AZIMUTH AND ELEVATION GUIDANCE FROM SCANNING BEAMS	CURVED OR LINEAR	LIMITED (TO ±24° AT PRESENT)	GOOD	HIGH	NONE	12 APPROX	LOW

Figure 111: Major Features of Alternative Landing Aids Available

SYSTEM A DME FOR AZIMUTH FIXED MICROWAVE BEAM FOR ELEVATION	SYSTEM B FIXED MICROWAVE BEAM FOR BOTH AZIMUTH AND ELEVATION
ADVANTAGES o ALL-AZIMUTH APPROACH o GROUND MANEUVER ABILITY WITHOUT INTERFACE WITH EXTRA SYSTEM DISADVANTAGES o HIGHER COST THAN SYSTEM B o IMPLIES TWO GUIDANCE SYSTEMS (DUPLICATION OF EQUIPMENT) o ELEVATION APPROACH PROFILE FIXED AND LINEAR	ADVANTAGES o LOWER COST THAN SYSTEM A o SINGLE SYSTEM FOR BOTH GUIDANCE FUNCTIONS DISADVANTAGES o ELEVATION AND AZIMUTH APPROACH PROFILE FIXED AND LINEAR o NO GROUND MANEUVER ABILITY o NUMBER OF AZIMUTH APPROACH DIRECTIONS SAME AS NUMBER OF TRANSMITTERS

Figure 112: Alternative Systems for Final Selection

Approach and Takeoff Profiles

The VTOL takeoff and landing profiles will probably be chosen to provide the best compromise of the many parameters involved. To do this may require a high degree of blending and mixing of control parameters.

Such a blending will be an order more difficult than the controlling of conventional aircraft. This latter point, when combined with the requirement for extreme regularity under both VFR and IFR in order to fit into an automated ATC system, points to almost exclusive use of a fully automatic, highly reliable landing/takeoff system. The pilot would act as monitor and would be required to take over control if the automatic system fails.

The general requirements for flight trajectories include avoidance of trajectories that cause high longitudinal decelerations near touchdown, because these decelerations give the pilot no time to correct a late failure of the automatic system and also require the pilot to manipulate too many controls in too complex a manner. Flight profiles are also limited by factors of minimum flight time, minimum fuel consumption, and passenger comfort. The general conclusion reached is that the 1985 short-haul system will be using steeper descent paths (in V/STOL modes) than the 3° to 6° paths presently being flown. In the aircraft performance and noise abatement maneuver studies reported elsewhere in this report, angles up to 20° are exercised and are shown to be desirable.

Ground Terminal Layout

Factors affecting the landing pad configuration are:

- Dimensions of the aircraft
- Accuracy of the guidance system
- Errors as a result of wind gusts and shear
- Ground roll

From the aspect of instrumentation and landing aid requirements, the following assumptions are made. The accuracy of DME based on the STATE landing system is given as ±10 ft (3 m). This will be taken as typical. Aircraft control system error will be taken as ±5 ft (1.5 m). This figure, which was obtained from simulation of VTOL aircraft automatic landing systems, may be attributed to nonlinearities in the control system. The response of the aircraft to wind is difficult to evaluate. The Brookhaven National Laboratory has taken measurements indicating that wind shear is less than 4 kn per 100 ft (2 mps per 30 m) for 99.6 percent of the time, and that it does not exceed 5 kn per 100 ft. If a wind shear of 4 kn per 100 ft is assumed to go uncorrected over the last 100 ft (30.5 m) of descent, this will lead to an error of approximately ±33 ft (10 m) in touchdown position if the aircraft mean descent rate is 10 fps (3 mps). A sharp-edged gust of 15 fps (4.6 mps) applied to the aircraft 2 sec before touchdown will result in some error less than 30 ft (9.15 m). The ground roll of the aircraft will be minimal and should be controllable to less than 10 ft (3 m). The total landing tolerance is therefore comprised as follows:

Guidance system accuracy	±10 ft (3 m)
Control system error	± 5 ft (1.5 m)
Wind shear error	±33 ft (10 m)
Wind gust error	±30 ft (9 m)
Ground roll	10 ft (3 m)

The use of coded data landing aids operating at the same carrier frequency eliminates any landing aid separation requirements, because they can be separated by any large or small distance. The use of DME in conjunction with a number of ground based transponders (greater than three) will allow precision measurement of distance, both in the air and on the ground. DME can be made to provide measurements down to less than 1 ft (0.3 m). Thus, if the layout of VTOL terminal sites is standardized so that the geometrical relationship of landing sites, transponders, and passenger embarkation points is the same for all terminals, the pilot will be able to navigate himself with precision all the way to the loading ramp.

The use of redundant transponders will allow adequate all-weather mobility and provide a check against transponder failure. There is no restriction on transponder layout; transponders may be placed in almost any pattern and in any number. It is also unnecessary for aircraft ground operations to be within the transponder pattern.

Flight Controls

Since VTOL aircraft are, in general, inherently unstable, they require a combination of aerodynamic and reaction control systems to maneuver during all phases of flight. VTOL aircraft lack inherent stability in the transition and hover flight modes and during transition will often exhibit strong interaxis aerodynamic coupling as well as crosscoupling between axes of the flight control system.

These characteristics and others make a stability augmentation system (SAS) necessary for safe, efficient flight. The advantages that accrue from inclusion of an augmentation function are:

- An inherently unstable vehicle can be made stable and be given good handling characteristics
- Effects of both aerodynamic and control couplings can be minimized
- Pilot workload can be reduced significantly
- Perturbations as a result of engine or control failure can be reduced

Having established the requirements for a SAS, it is then necessary to determine which system variable the pilot would wish to command. Without stability augmentation, the pilot commands angular acceleration that is two derivatives higher than angular position and that is probably two orders more difficult to fly in certain situations. Even if the pilot has direct control of angular attitude, he would still only be able to command translational acceleration. It is apparent that during the last part of transition and hover, he is attempting to control translational position. These basic dynamic characteristics show the value of utilizing the SAS to allow direct control of a system variable of considerably lower derivative order than basic angular acceleration. Boeing studies have been conducted on a fixed-base simulator utilizing a moving, external-world, visual display in an attempt to decide which derivative of attitude or translation should be commanded. This work indicates the value of an (angular) attitude control system for the transition mode. As a result, it is concluded that attitude control in both pitch and roll axes combined with yaw rate control would constitute a suitable SAS. These results have also been verified on the NASA Ames moving-base simulator.

The case for either translational velocity or position command modes is not easy to establish. The following factors are involved:

- Sensed parameters must be referenced to ground, but may also need to be referenced to air, in order to wash out turbulence and wind shear effects.
- The system is essentially an automatic control loop and therefore more than just part of the SAS.
- Additional pilot controls may be required. These may be tolerable in large aircraft but are impossible for small aircraft. Mixing of control functions on a single control lever must be viewed with caution because of the possibility of pilot confusion.
- The mode must be blended with others more appropriate to other flight conditions.

The use of an altitude damping mode has also been investigated and was found to be unnecessary for the particular aircraft considered because it had adequate inherent damping. However, this question must be decided for each particular aircraft configuration investigated, bearing in mind the improvement in passenger comfort (as a result of the softer touchdown) that this mode provides.

The introduction of fly-by-wire (FBW) control systems will simplify the problem of control mixing. A simple, uncompensated mechanical system would perhaps be retained as a backup during conventional flight. FBW systems are being used on some aircraft engine controls, particularly in England. Several American engine companies are conducting studies in this area. The pitch, roll, and yaw axes could use a simple mechanical system with a series SAS actuator inserting commands. The thrust computer could be entirely FBW except for gross collective thrust changes. By 1985, FBW techniques will have had 15 to 20 years of development and their role in aircraft control design should be well established.

A degree of redundancy is required so that the electrical system may be highly reliable. Furthermore, the design should be such that a single failure does not affect the performance of the equipment, (i. e. it should be fail-operational) and such that double failure in the system would cause it to shut down automatically without violent transients. The equipment must therefore "fail soft" for second failures. The redundancy can consist of a dual channel system with a model to allow comparisons to be made at various points in the equipment, or a fully triplicated system that allows the working channel or channels to override a failed channel. This may be achieved in various ways, but the method of median selection by voting is most preferred. This method requires a monitor to

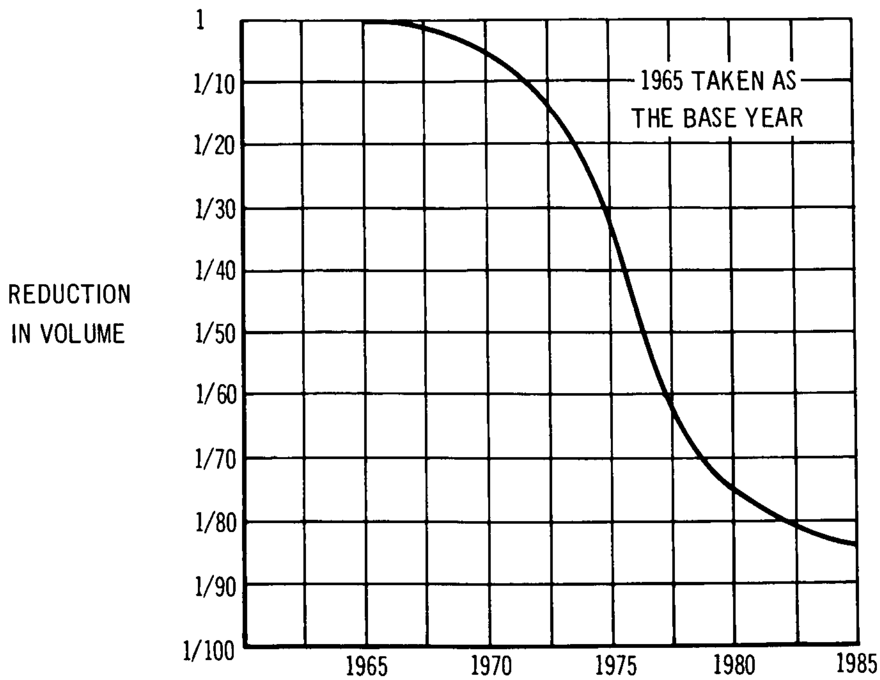


Figure 113: Avionic Equipment Volume Reduction

pick up second failures and shut down the system. A higher degree of redundancy may also become available. Tradeoff studies between these redundancy schemes would need to be carried out to determine which alternative is best suited to any particular control system and aircraft.

It is not good practice to design and build a fully reliable SAS without supplying equally reliable inputs to the SAS system. Thus both the attitude and air data sources must be redundant. The required failure protection is obtained by using at least triple-redundant sources and voting techniques to select correct information. The necessary development of redundant systems and the techniques of stability augmentation is at present underway. The development of short-haul transport electronics in the period prior to 1985 will therefore use proved techniques and equipment.

Communication and Navigation Equipment Trends Through 1985

The size and reliability of aviation electronics depend on new developments in circuit components, packaging techniques, and system integration. At the same time that the units are made smaller, lighter, and less power-consuming, they must be made more reliable. Integrated electronics are expected to have a very significant effect on avionic subsystems by 1985. The very small size and low weight of microcircuitry will greatly decrease overall size and weight of avionic subsystems, while the high reliability of microcircuitry will increase the reliability of the subsystem.

Figure 113 shows a prediction of the size of future avionic subsystems as compared with today's. This assumes that there is no increase in functional capability. The trend to smaller sizes will begin to level off in the 1980's because a high percentage of each communication and navigation subsystem will have already incorporated integrated electronics. The high component density of the small units will require appropriate cooling methods to limit ambient operating temperatures.

The increasing reliability of avionic equipment through use of integrated electronics is shown in fig. 114. By 1985 some communication/navigation equipment will have a mean-time-between-failures of more than 20 000 hours. This is approaching the ultimate goal, that the avionic equipment last the life of the aircraft with no maintenance required.

The large reductions in size and the increases in reliability will in part be absorbed by increases in functional capability. The units will be designed so that they can test themselves and indicate failures to the flight crew. Special outputs and computing abilities may also be included.

Another aspect of avionics that lends itself to integration is the similar circuit functions in many of the communication and navigation equipments. The RF receiving circuits and power supplies are two examples of this concept. For instance, with the DME interrogator and ATC transponder, the RF receiving circuitry may be designed with a bandwidth compatible with their respective frequency requirements, so that one RF receiver could be used for both the subsystems. This would eliminate many components and would make the subsystems lighter, smaller, less power-consuming, and more reliable.

Air Routes and Conflicts

The third area of review is an analysis of air routes and the description of the 1985 air traffic control system. Typically, a terminal area consisting of a circle of 10 nautical miles (18.5 km) in radius centered on a landing spot was examined with respect to the routes to the other terminals in the system to determine what interferences existed and what flight levels could be maintained in the airport control area. It was established that while each terminal area must be analyzed separately, routes could be established between terminals in a route system that could be flown point-to-point. It also was apparent that CTOL aircraft in 1985 might have the same holding problems that exist today unless significant changes are to be made, for instance in the acceptance capabilities of CTOL airports. The flightpath profiles in and around landing points must be considered individually, especially in the STOL and VTOL cases, because these would probably require new facilities located in densely populated areas. It is concluded that an altitude-limited approach to avoid conventional airport ILS beams is unnecessary. The routing that allows for an immediate climb profile generally results in a negligible increase in point-to-point distance.

Air Traffic Control (ATC) System

The 1985 ATC is hypothesized. The typical ATC environment resembles the 1966 system with the following exceptions:

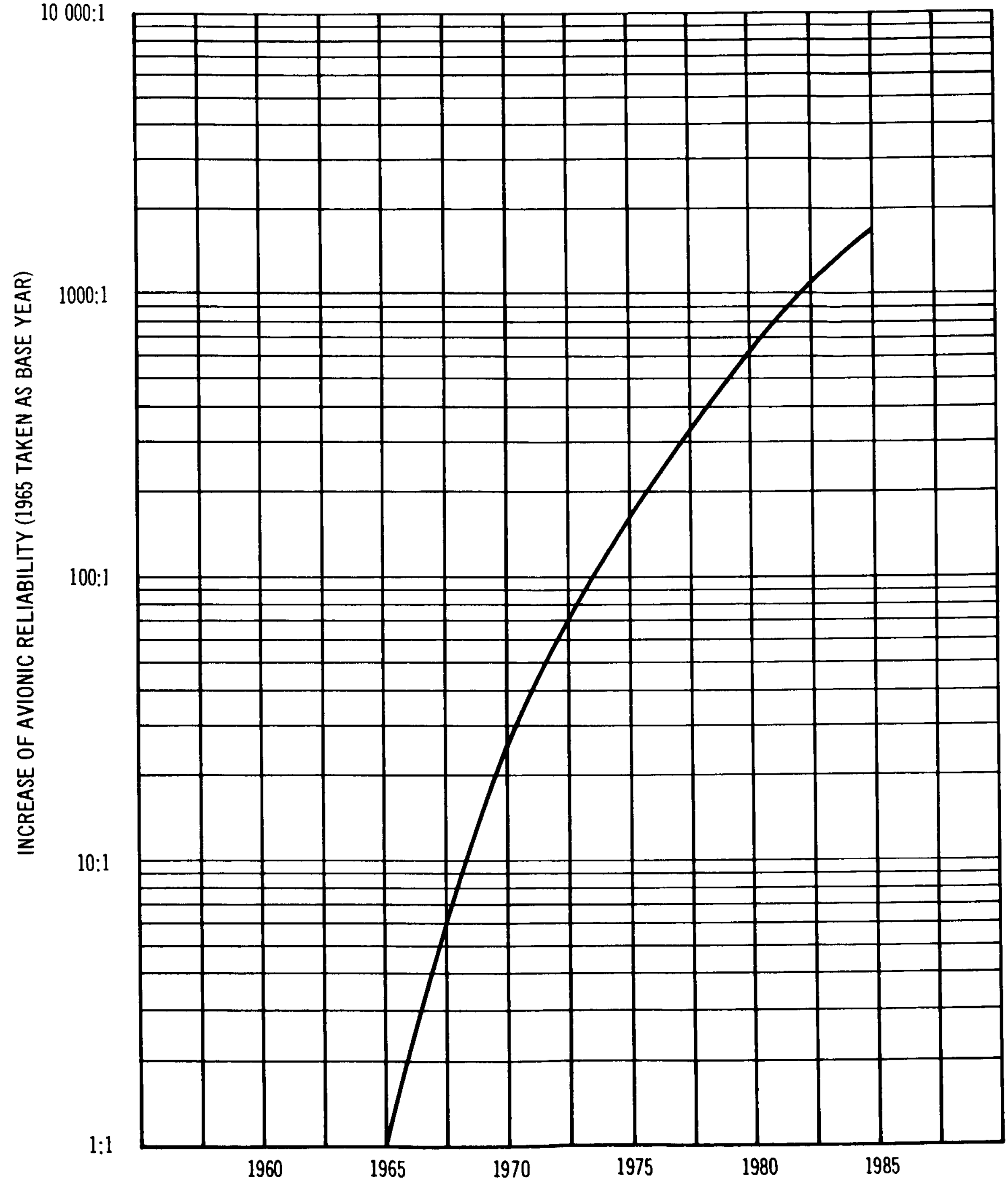


Figure 114: Increase of Avionics Reliability With 1965 as Base Year

- The 1985 ATC system will be more automated. Manual conflict prediction and resolution, manual identification and monitoring, and manual inter-ATC center coordination will be replaced by computer conflict prediction and resolution, automatic identification and tracking, and computer-controlled intercenter coordination.
- The radar display used by the ground controller will use alphanumeric representations for the aircraft position, identification, and various items of flight information such as transponder codes, actual altitudes, altitude for which the aircraft is cleared, and bookkeeping data.
- By 1985, the ATC system will be modified to allow for mosaic displays that will be radar displays using outputs from several radars optimized to give the best combinations of information available to the ATC operator.
- Communications between the ATC operator and pilot will be by digitized data link for all routine transfers of data. With the implementation of an alphanumeric cockpit display and an operator's keyboard, the routine flight and ATC information will be transmitted back and forth (and confirmed by the receiver) in considerably less time than is possible today. This reduction in ATC operator and pilot workload will be accompanied by a corresponding reduction in RF spectrum use requirements.

These postulated changes in the ATC environment are based upon predictions supplied by the FAA. Certain forcing factors such as the proposed future large subsonic and supersonic aircraft may produce changes in the ATC environment that exceed the predictions of the FAA. These changes might include higher degrees of automation in the ATC data handling equipment and the placing of certain additional controls or restrictions on the use of airspace.

SUMMARY

The postulated changes in ATC, communication, navigation, and landing systems have been outlined. The areas that require further research and development are summarized as follows:

Landing Aids

The aircraft, VTOL or STOL, will require a stability augmentation system and automatic landing system that may well be triple-redundant with majority voting logic between channels.

The advantage and disadvantages of the two landing aids concepts proposed are shown in fig. 112. A tradeoff study could be implemented when more detail is available on the azimuth operational requirements. Steep descent paths require further work to establish the acceptability of approach angles greater than the 3° to 6° (0.052 to 0.105 rad) presently being flown. Techniques, instrumentation, and training methods that allow the pilot to fly a glide path greater than 6° to 9° (0.105 to 0.157 rad) must be established.

Navigational Aids

This review shows that the 1985 short-haul system will fly with a developed form of a present navigation system.

Ground Terminal Layout

The existing technology is sufficient to the problem of designing new ground terminals.

Flight Controls

The case for or against translational command modes versus attitude command modes has not been clearly defined. The need for such modes must be established and the problems of what controls the pilot should use, and in what way they should be combined with the more familiar control functions, must be solved.

Equipment Physical Characteristics

The use of improved packaging techniques and improved materials may reduce the physical size and weight of the avionic equipment. While power consumption is not a critical item, reduction in unit size may bring about a reduction in power consumed. The reliability of all electronic units should be improved. Other developments necessary are self-monitoring and push-to-test functions.

Air Routes and Conflicts

Unless significant changes are made in today's terminal acceptance capabilities, the short-haul system will suffer from excessive holding times.

Air Traffic Control System

The postulated ATC system for 1985 is based on the assumption of an orderly evolution from the ATC of today. If the growth of air traffic matches FAA predictions, no problems in ATC procedures, operation, and regulations are foreseen.

FAA bases its future plans on the expected changes in aircraft count and the operations associated with those aircraft. Therefore, for an efficient ATC system in 1985, accurate estimates of growth that are continually updated are essential to guide the development plans.

7.1.2 Configuration determination. — To serve as a starting point for this study, a number of design assumptions were made, mission profiles described, and ground rules set. The following sections cover these assumptions, present the aircraft characteristics that followed, discuss the concepts considered, describe the various sensitivity studies that were made, and discuss the overall results prior to making the selection of vehicles for the systems analysis.

Using the established technology levels as outlined in the previous section, the sizing of the various configurations of each concept was accomplished by extensive use of engine-aircraft matching computer programs.

The sensitivity studies concerning cruise speed, cruise altitude, and installed T/W, for example, are used to improve upon the initial set of mission and aircraft assumptions so that the aircraft considered for analysis in the route system are the minimum operating cost designs of each concept.

7.1.2.1 Design assumptions. — A number of initial design assumptions were made that are common to all concepts. The passenger seating is intended to offer the same comfort level as today's economy seats. An improvement in seats would allow this to be accomplished with a seat pitch of 32 in. (0.814 m). All capacities were originally considered to have six-abreast seating with a 20-in. (0.51-m) aisle. All aircraft bodies would be configured using the latest requirements for evacuation. The body would be circular in cross-section, with a diameter of 148 in. (3.76 m).

At the 200-passenger level, eight-abreast seating was considered, with the final configurations of the jet lift and folding tilt rotor concepts incorporating this interior.

As complete meals would probably not be served on these short-range flights, food service was limited to one minimum-size galley (two for 200 passengers). Two toilets were included for passenger capacities up through 120, with four toilets included for the 200-passenger airplanes. One attendant per 60 passengers is the ratio for stewardesses.

All concepts have been designed with self-contained systems to operate with a minimum of ground support. One main door forward and one aft have integral stairs, although in the design of the terminal different features are considered. An auxiliary power unit is installed for ground use as well as for emergency system power in flight.

The weight of one passenger plus baggage was assumed to be 200 pounds (91 kg). The design payload did not allow for additional cargo.

The flight deck is designed for a crew of two.

The design cabin pressure differential was set at 7.85 psi (54 000 n/m^2), which gives a 5000-ft (1530-m) cabin altitude at a 30 000-ft (9150-m) cruise altitude. A 300-ft/min (1.52-mps) limit on rate of change of cabin altitude did not limit the performance of any concept at cruise altitudes below 25 000 ft (7630 m).

7.1.2.2 Mission profiles. —At the short ranges indicated in this study, the minimum DOC cruise altitude is at the altitude for balanced range (the cruise distance is half of the total range).

Climb speed is set at 380 kn EAS (195 mps) and descent at the placard speed. Descent at the placard is well established as being a minimum DOC operation. Several checks showed the 380-kn EAS climb to be within 0.25% of the minimum DOC speed except for the tilt wing, which climbed at best rate of climb subject to a cabin floor angle limit of 12 degrees (0.2 rad).

Ground maneuver time for the conventional aircraft is set at 15 min (11 min taxi out, 4 min taxi in), considered to be typical of the big airports if no attempt is made to improve the present situation. The effect of reducing this time is shown in the sensitivity studies. For the STOL concepts ground maneuver time is reduced to 2 min total, and for the VTOL concepts 1 min, based on the assumption that the respective ports will be designed and operated specifically for this traffic, and hence taxi distances will be small and waiting time reduced.

The takeoff time allotted for each concept is 1 min. This covers the time from the start of takeoff until distance credit begins. This occurs 1 nmi (1.85 km) for VTOL concepts and 2 nmi (3.7 km) out for STOL and CTOL concepts.

Air maneuver time for the CTOL is 6 min, with a reduced time being considered in the sensitivity studies. The air maneuver time is 2.5 min for the STOL concepts and 2 min for the VTOL concepts.

The landing time for the VTOL concepts is 2 min and accounts for 2.5 nmi (4.6 km) from the point where distance credit ends until touchdown. The STOL concepts use 2.5 min and 3.25 nmi (6.00 km), and the CTOL uses 4.5 min and 6.5 nmi (12 km) from the last point of distance credit to touchdown.

The reserves allow for a diversion distance of 200 nmi (370 km) for the CTOL and 100 nmi (185 km) for the VTOL and STOL concepts. The climb for reserves commences at 1500 ft (456 m) and is a low-speed climb for maximum range. Cruise is done at 20 000-ft (6100-m) altitude at long-range cruise speed, and no descent is included. The STOL and CTOL concepts have in addition fuel reserves for holding at 1500-ft (456-m) altitude for 15 min for the STOL and 30 min for the CTOL.

7.1.2.3 Ground rules. —Takeoff performance for all concepts is based on a sea level, hot day (89°F or 304°K) condition. However, all mission performance is based on standard day conditions.

Takeoff power is at 100% of design turbine inlet temperature. For engine-out conditions, a contingency rating of 1.07 times takeoff power may be used for a maximum of 2.5 min. Climb power is at 97% of design engine speed (rpm) and cruise power at 95% (approximately 12% reduction in thrust).

The powerplant design parameters were taken from the cycle study described in sec. 7.1.1.2. Initially, bypass ratio 3 cruise engines were used, but noise considerations led to the use of bypass ratio 5 for lift engines as well as cruise engines. All engines have a turbine inlet temperature of 2800°R (1560°K). The cruise turbofans have a pressure ratio of 20 and produce approximately 11 lb of static thrust per pound of engine weight (108 n/kg) under sea level standard day conditions. The lift turbofans of the same pressure ratio have a thrust-to-weight ratio of 23. The lift fans for the fan-in-wing concept, both concentric and tip-driven, have a bypass ratio of 10, a pressure ratio of 12, and thrust-to-weight ratio of approximately 15.

The installed vertical thrust margin (hot day) for all VTOL concepts is as follows:

All engines —	no control input	1.15
	control input = 100% one axis, 50% other axes	1.05
Engine out —	no control input	1.05
	control input = 50% one axis, 20% other axes	1.00

All vertical thrust margins are for a trimmed airplane with the most adverse center-of-gravity position.

The corresponding (100%) attitude control requirements for the VTOL are listed as follows, including CTOL and STOL requirements:

	Roll	Yaw	Pitch
VTOL	0.6 rad/sec^2	0.4 rad/sec^2	0.25 rad/sec^2
STOL	0.45 rad/sec^2	0.4 rad/sec^2	0.20 rad/sec^2
CTOL	0.40 rad/sec^2	0.4 rad/sec^2	0.20 rad/sec^2

The takeoff and landing field lengths for the STOL concepts were calculated using variable rules. In the case of the high-acceleration STOL, a conservative approach was taken with the following rules: maximum vertical velocity = 12 fps (3.6 mps) (approach angle = 5.50 deg); 0.5 g maximum deceleration; and a landing field length factor of 1.4 times landing distance. This approach yields a field length of 1680 ft (512 m). Increasing the approach angle to 12 deg and assuming a 0.2 g flare to touchdown at 4 fps (1.2 mps) reduces the field length to 1400 ft (425 m). Increasing the maximum allowable deceleration to 1 g further reduces the distance by 300 ft (92 m). Throughout this study the conservative field length of 1680 ft (512 m) will be listed.

A similar variation in rules for the high-lift STOL shows that the downtown STOL with a listed field length of 1650 ft (503 m) could possibly have a field length 200 ft (61 m) less; the range of field lengths for the suburb STOL goes from 1900 to 2200 ft (580 to 671 m).

All of the above field lengths, however, are based on the same approach speed, that which will give an all-engine maneuver margin of 0.44 g or an engine-out maneuver margin of 0.33 g. This margin requirement was the subject of much discussion and deserves more study in the future. The problem arises because of the dependence of a substantial portion of aircraft lift on engine thrust. For the high-acceleration STOL, if the approach were made at 1.3 times the stall speed with all engines operating, the maneuver margin would be only 0.13 g instead of the nearly 0.5 g available on current (nonpowered-lift) aircraft at 1.3 times the stall speed.

7.1.2.4 Summary of aircraft characteristics. — To cover all of the anticipated range and capacity requirements, 16 aircraft were initially designed for each concept. Design ranges were 150, 300, 500, and 700 nmi (278, 556, 928, and 1300 km). Design passenger capacities were 60, 90, 120, and 200. Initial analysis of these aircraft over the route systems assumed indicated that three capacities (90, 120, and 200) at one design range of 300 nmi (556 km) satisfied the system's demand. Selection of one design point range was done after considering the city-pair distances, the effects of winds on aircraft performance, the simplified payload-range curves of each concept (see fig. 120) and a preliminary total profit evaluation.

A summary of the more important characteristics of the concepts selected for final analysis is shown in table 7 . The weight statements for the final optimized aircraft of each concept are shown in tables 8 and 9

Table 7: General Characteristics Summary

	Concentric Fan	Jet Lift	Hi-Accel STOL	Hi-Lift (w/s=60) STOL	Hi-Lift (w/s=90) STOL	CTOL (6 Min. AMT)	Folding Tilt Rotor	Tilt Wing	Helicopter
Design Field Length* (ft)	VTOL	VTOL	1680	1650	2200	6000	VTOL	VTOL	VTOL
$C_{L_{MAX}}$	2.0	3.3	4.7	6.7	6.7	3.3	2.3	---	---
w/s	100/85/80	180/170/165	100	60	90	105	120	100	---
Disc Loading (psf)	---	---	---	---	---	---	22	50	13.3
Aspect Ratio	3.5/3.2/3.1	7	8.5	8.5	8.5	8.5	6.08	9.1	---
Λ C/4 (deg)	35	30	25	25	25	25	0	0	---
(t/c) Average	0.105	0.105	0.105	0.105	0.105	0.105	0.100	0.140	---
No. of Rotors	---	---	---	---	---	---	2	4	2
No. of Blades/Rotor	---	---	---	---	---	---	3	3	4
Solidity	---	---	---	---	---	---	0.09	0.226	0.093
Tip Speed (fps)	---	---	---	---	---	---	830	850	740
No. of Cruise Engines	2	4	2	4	4	2	2	4	4
Cruise T/W	0.45	0.34	0.31	0.37	0.37	0.33	0.398	---	---
No. of Lift Engines	4	8	4	---	---	---	---	---	---
Lift T/W	0.554	1.137	0.905	---	---	---	---	---	---
No. of Gas Generators for Reaction Control	2	---	---	---	---	---	---	---	---
Reaction Control T/W	0.3	---	---	---	---	---	---	---	---
Total T/W	1.304	1.477	1.215	0.37	0.37	0.33	0.398	---	---
Placard (KEAS)	420	430	430	300	400	430	430	400	250
N_{GUST} (max at V_{MO})	2.41	2.22	3.18	2.90	3.13	3.21	2.69	2.90	---
M_{cruise}	0.96	0.93	0.9	0.745	0.9	0.9	0.87	0.777	0.412
M_{CRIT}	0.953	0.911	0.903	0.903	0.902	0.901	0.886	0.775	---
$V_{APPROACH}$(KEAS)	---	---	73	67	79	126	---	---	---
$V_{CONVERSION}$ (KEAS)	154	161	103	---	---	---	158	150	---
Payload/GW	0.337	0.357	0.335	0.365	0.370	0.390	0.285	0.3	0.317

*One engine out 89°F

	Design Capacity									
Cruise Thrust in lb (or HP) per Engine	90 120 200	13 500 16 900 26 700	4 760 6 020 9 550	9 230 11 700 18 600	5 170 6 570 10 420	5 000 6 290 10 000	8 500 10 600 17 000	13 100 16 610 27 210	5 910(HP) 7 450(HP) 12 310(HP)	3 750(HP) 4 320(HP) 5 950(HP)
Thrust per Lift Engine (lb)	90 120 200	8 310 10 400 16 400	8 000 10 000 15 930	13 450 17 100 27 050	---	---	---	---	---	---
Rotor Diameter (ft)	90 120 200	---	---	---	---	---	---	45 49 63	20 23 29	58 64 88
Overall Length (ft)	90 120 200	86 101 147	106 123 140	86 101 147	88 111 152	88 111 152	86 101 147	85 103 134	84 102 132	115 134 173
Wing Span (ft)	90 120 200	48 54 64	50 54 65	71 81 100	89 101 125	71 82 100	64 72 90	58 65 84	76 86 110	--- --- ---

Table 8: Weight Summary—All Concepts, 120-Passenger Capacity

120 PASSENGERS

	Conventional	STOL Hi-Accel	STOL Hi-Lift 1650 F. L.	STOL Hi-Lift 2200 F. L.	VTOL Jet Lift	VTOL Concentric Fan-In-Wing	VTOL Folding Tilt Rotor	VTOL Tilt Wing
Wing	3 650	5 000	7 670	5 250	2 550	3 180	3 560	4 400
Rotor							5 190	
Tail	1 200	1 430	2 220	1 720	810	1 330	1 820	1 700
Body	7 370	8 220	7 740	7 690	8 730	7 520	7 580	8 190
Landing Gear	2 000	2 460	2 590	2 500	2 290	2 480	2 770	2 590
Nacelles	890	5 630	1 140	1 100	2 760	2 990	1 870	1 360
(Structure)	(15 110)	(22 740)	(21 360)	(18 260)	(17 140)	(17 500)	(22 790)	(18 240)
Lift Fans						3 140		
Cruise Engines	2 060	2 280	2 450	2 370	2 250	3 140	3 270	3 010
Lift Engines		3 030			3 530			
Engine Controls	60	140	120	120	360	180	200	200
Fuel System	750	590	550	570	570	600	590	590
Starting System	120	180	240	240	360	180	120	240
Lubrication System							50	80
Propellers							*110	3 890
Drive System							6 590	4 540
(Powerplant)	(2 990)	(6 220)	(3 360)	(3 300)	(7 070)	(7 240)	(10 930)	(12 550)
Instruments	540	570	550	550	620	570	540	540
Flight Controls	1 010	1 070	2 080	1 700	940	1 200	3 470	4 220
Hydraulics	250	350	370	310	320	310	380	400
Electrical	1 570	1 570	1 570	1 570	1 570	1 570	1 570	1 570
Electronics	540	540	540	540	540	540	540	540
Furnishings	6 780	7 230	6 850	6 850	7 380	6 960	7 150	7 150
Air Cond., Anti-Ice	1 770	1 820	1 800	1 800	1 900	1 820	1 940	1 940
APU	770	770	770	770	770	770	770	770
Aux Gear Grp	40	40	40	40	40	40	40	40
Reaction Control						3 280	280	
(Fixed Equipment)	(13 270)	(13 960)	(14 570)	(14 130)	(14 080)	(17 060)	(16 680)	(17 170)
Weight Empty	31 370	42 920	39 290	35 690	38 290	41 800	50 400	47 960
Crew and Baggage	660	660	660	660	660	660	660	660
Unusable Fuel & Oil	390	490	470	470	690	490	390	470
Passenger Service	790	790	790	790	790	790	790	790
(Useful Load)	(1 840)	(1 940)	(1 920)	(1 920)	(2 140)	(1 940)	(1 840)	(1 920)
Operating Wt. Empty	33 210	44 860	41 210	37 610	40 430	43 740	52 240	49 880
Passengers	19 800	19 800	19 800	19 800	19 800	19 800	19 800	19 800
Luggage & Cargo	4 200	4 200	4 200	4 200	4 200	4 200	4 200	4 200
Fuel	7 410	6 800	5 900	6 430	6 470	7 650	7 320	6 720
Gross Weight	64 620	75 660	71 110	68 040	70 900	75 392	83 560	80 600

*Exhaust & Cooling

Conversion factor for international units (lb x .454 = kg)

Table 9: Weight Summary—All Concepts, 200-Passenger Capacity

200 PASSENGERS

	Conven-tional	STOL Hi-Accel	STOL Hi-Lift 1650 F. L.	STOL Hi-Lift 2200 F. L.	VTOL Jet Lift	VTOL Concentric Fan-In-Wing	VTOL Folding Tilt Rotor	VTOL Tilt Wing	VTOL Heli-copter
Wing	6 340	8 500	12 550	8 720	4 340	5 420	6 850	7 690	
Rotor							9 660		7 690
Tail	2 070	2 350	3 630	2 790	1 360	1 920	2 700	2 680	*420
Body	11 220	12 600	11 500	11 430	13 520	11 460	11 900	13 040	8 500
Landing Gear	3 130	3 830	4 050	3 900	3 660	3 980	4 700	4 270	2 560
Nacelles	1 330	9 090	2 050	1 980	5 040	4 420	3 360	2 160	500
(Structure)	(24 090)	(36 370)	(33 780)	(28 820)	(27 920)	(27 200)	(39 170)	(29 840)	(19 670)
Lift Fans						3 940			
Cruise Engines	3 130	3 430	3 840	3 690	3 590	5 060	6 040	4 700	2 900
Lift Engines		4 720			5 640				**200
Engine Controls	60	140	120	120	360	180	200	250	180
Fuel System	850	690	660	690	690	740	750	750	800
Starting System	120	180	240	240	360	180	120	240	240
Lubrication System							80	120	100
Propellers								7 250	1 800
Drive System							12 140	8 400	11 740
(Powerplant)	(4 160)	(9 160)	(4 860)	(4 740)	(10 640)	(10 100)	(19 330)	(21 710)	(17 960)
Instruments	540	570	550	550	620	570	540	540	540
Flight Controls	1 230	1 300	2 960	2 370	1 040	1 350	6 510	7 910	8 850
Hydraulics	390	540	590	490	510	490	630	660	400
Electrical	1 750	1 750	1 750	1 750	1 750	1 750	1 750	1 750	1 750
Electronics	550	550	550	550	550	550	550	550	550
Furnishings	11 210	11 670	11 280	11 280	11 810	11 390	11 580	11 580	11 580
Air Cond., Anti-Ice	2 100	2 180	2 140	2 140	2 280	2 180	2 340	2 340	2 340
APU	1 100	1 100	1 100	1 100	1 100	1 100	1 100	1 100	1 100
Aux Gear Grp	40	40	40	40	40	40	40	40	40
Reaction Control						6 430	500		
(Fixed Equipment)	(18 910)	(19 700)	(20 960)	(20 270)	(19 700)	(25 850)	(25 540)	(26 470)	(27 150)
Weight Empty	47 160	65 230	59 600	53 830	58 260	63 150	84 040	78 020	64 780
Crew and Baggage	800	800	800	800	800	800	800	800	800
Unusable Fuel & Oil	550	710	650	650	890	670	550	650	650
Passenger Service	1 290	1 290	1 290	1 290	1 290	1 290	1 290	1 290	1 290
(Useful Load)	(2 640)	(2 800)	(2 740)	(2 740)	(2 980)	(2 760)	(2 640)	(2 740)	(2 740)
Operating Wt. Empty	49 800	68 030	62 340	56 570	61 240	65 910	86 680	80 760	67 520
Passengers	33 000	33 000	33 000	33 000	33 000	33 000	33 000	33 000	33 000
Luggage & Cargo	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000
Fuel	11 110	10 040	8 740	9 490	10 130	11 140	11 910	10 810	13 460
Gross Weight	100 910	118 070	111 080	106 060	111 370	117 050	138 590	131 570	120 980

*Pylon

**Air induction and exhaust

Conversion factor for international units (lb x .454 = kg)

Gross weight, OWE, and total installed thrust are plotted versus design capacity in figs. 115, 116, and 117. Fuel burned and block time are plotted versus range in figs. 118 and 119.

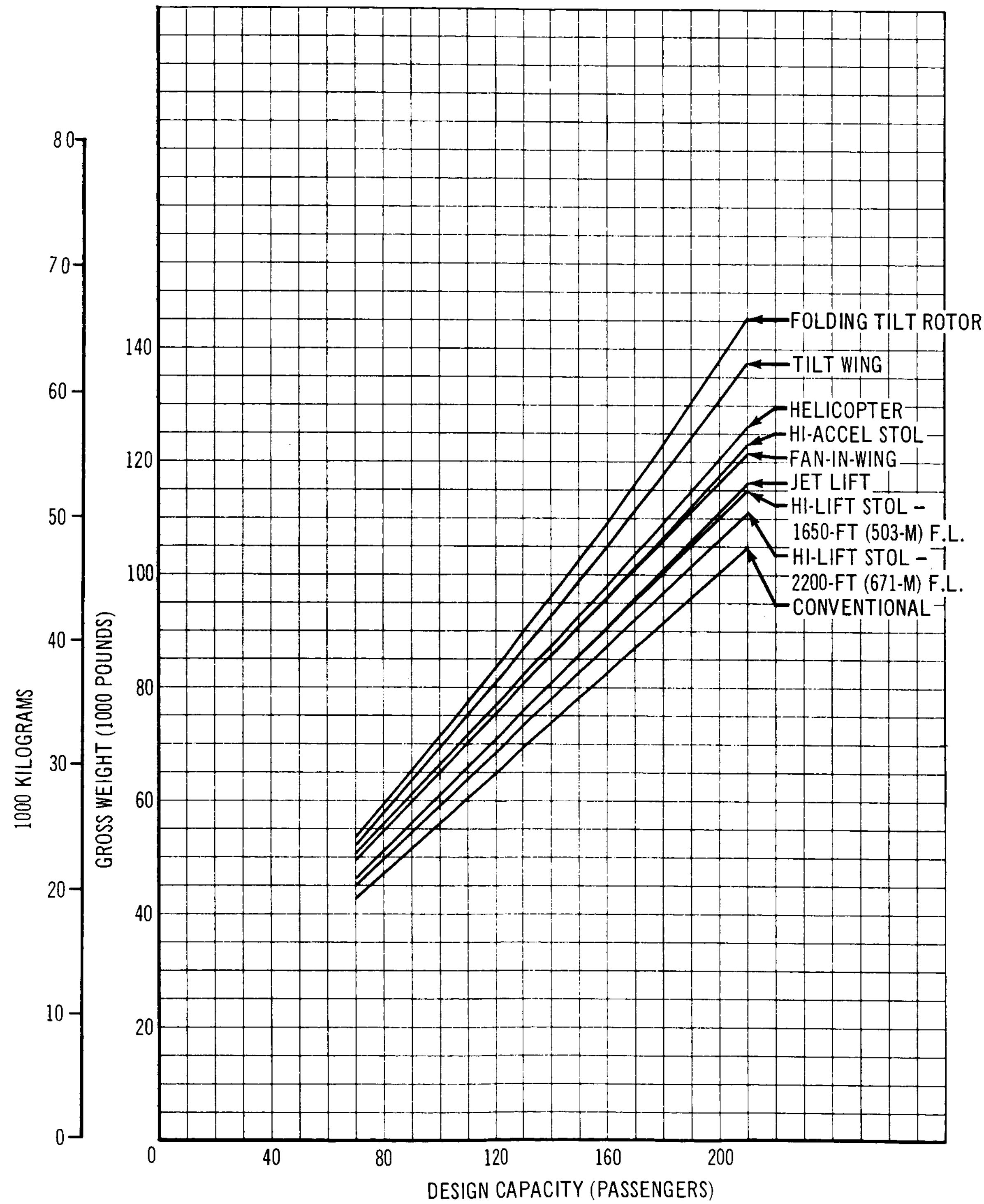


Figure 115: Gross Weight Versus Capacity—All Concepts

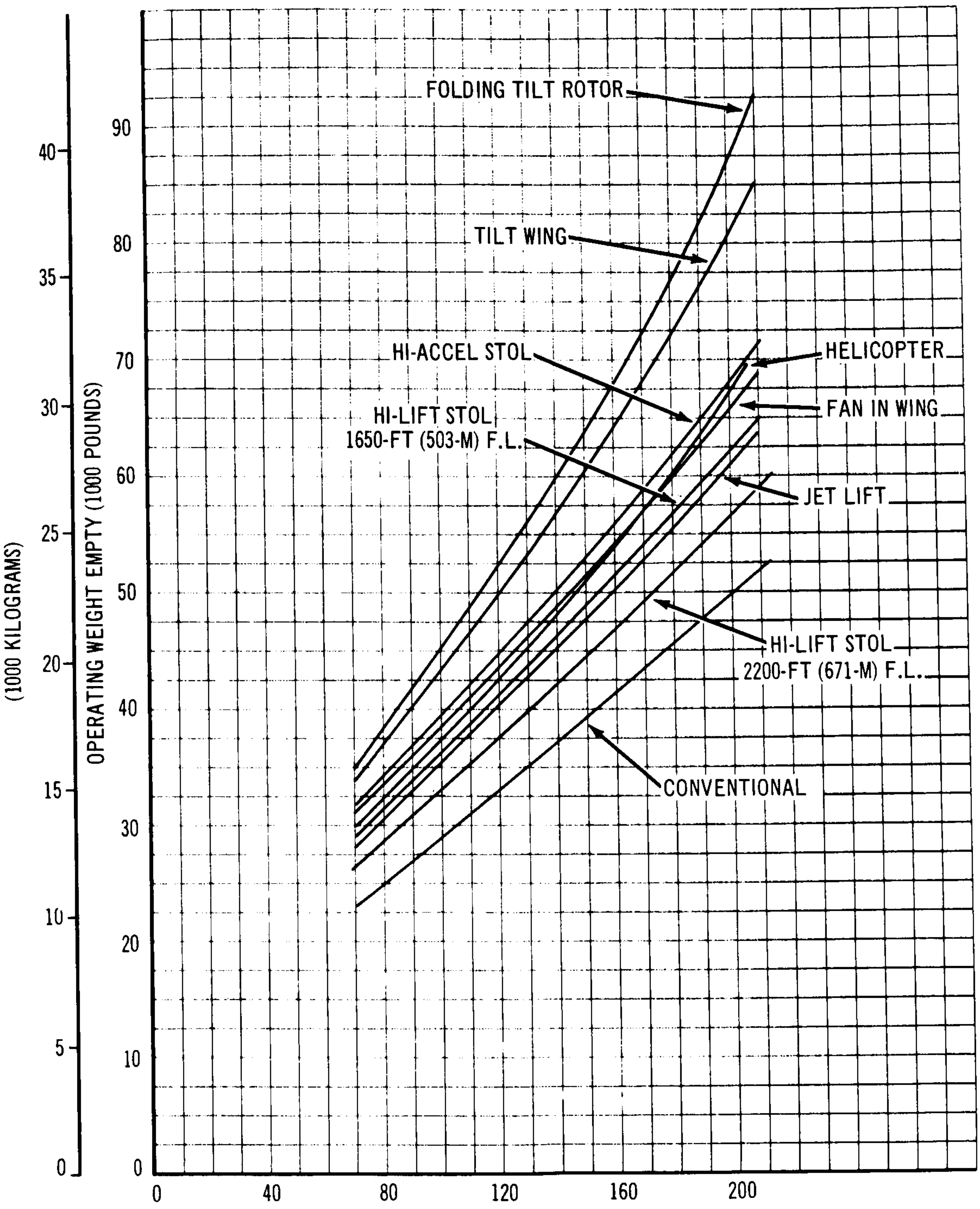


Figure 116: OWE Versus Capacity—All Concepts

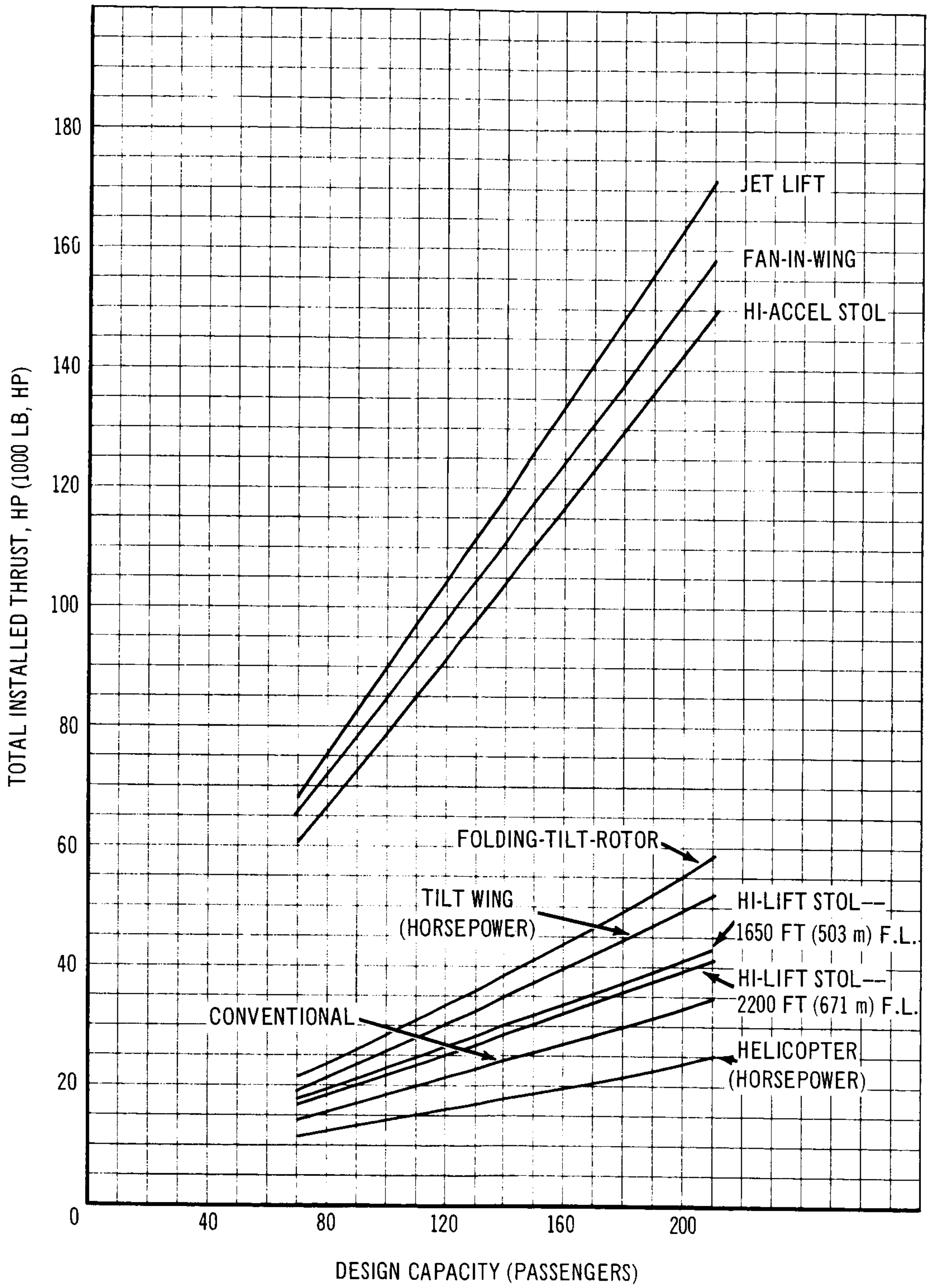


Figure 117: Total Thrust Versus Capacity—All Concepts

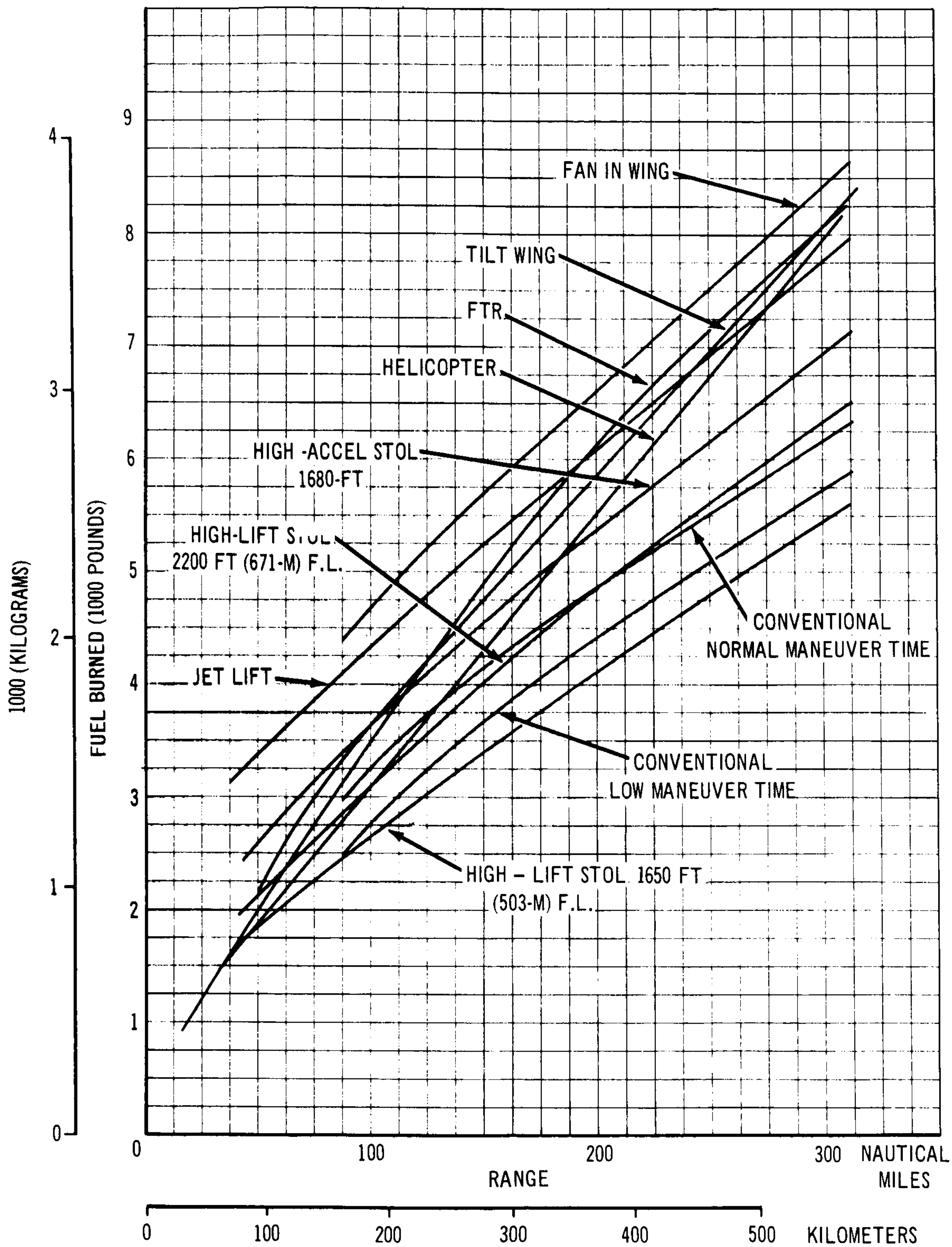


Figure 118: Fuel Burned Versus Range—All Concepts

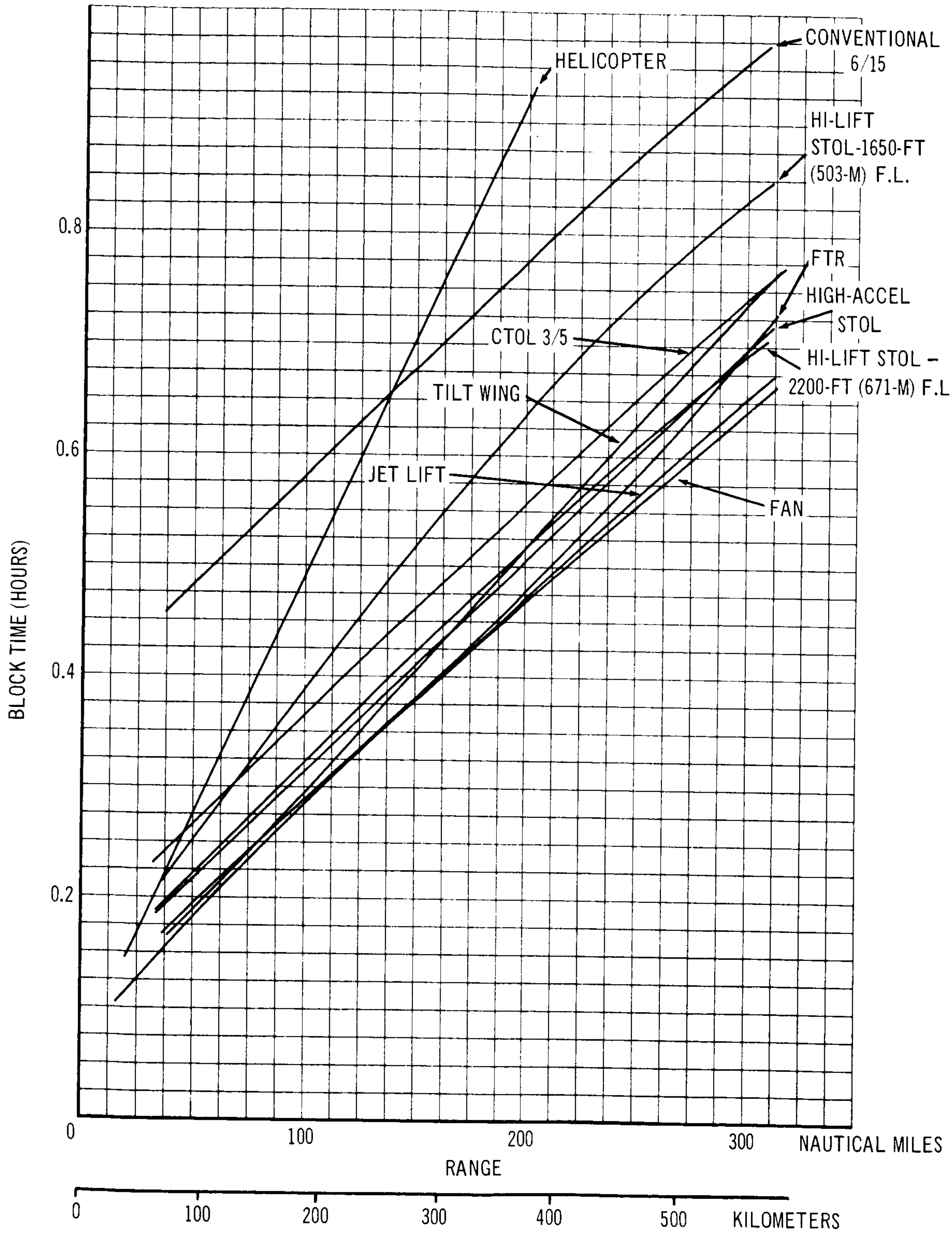


Figure 119: Block Time Versus Range—All Concepts

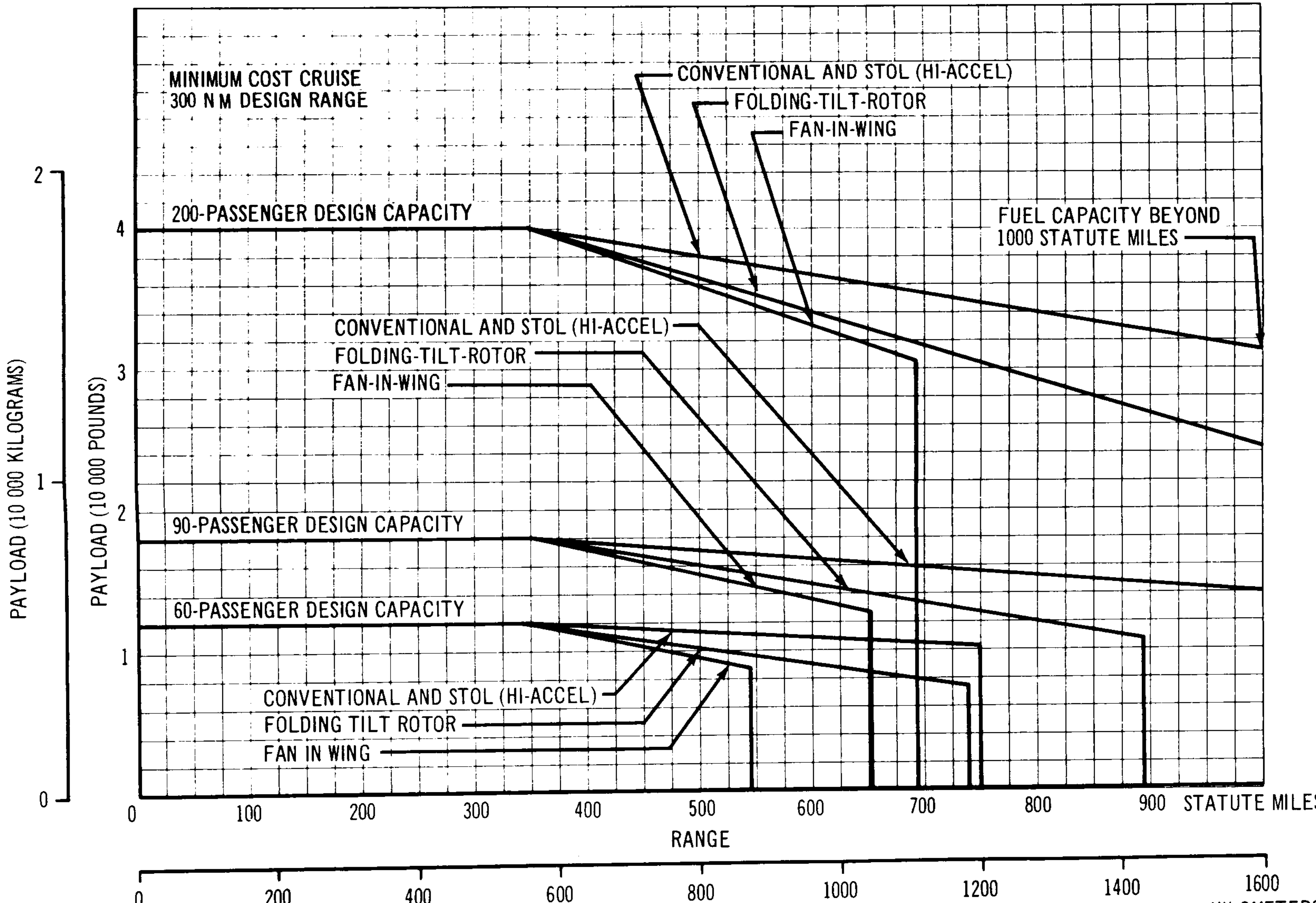


Figure 120: Payload-Range

7.1.2.5 Description of concepts.

7.1.2.5.1 Tilt wing: The tilt wing configuration is conventional in that it has four propellers and four turboshaft engines coupled by interconnecting shafting. Pitch control in hover is provided by monocyclic (single-axis-cyclic) control propellers augmented by wing tilt linked to longitudinal stick motion. Yaw control is provided by a spoiler deflector system and roll control by differential collective propeller blade angle. The complete vertical takeoff system is thus contained within the wing; there is no tail rotor, tail shafting, or aft gearbox.

A disk loading of 50 lb/ft^2 (245 kg/m^2) was chosen to give a power match between the engine-out hover requirement and the cruise condition. Using existing technology, this disk loading would normally be accompanied by a wing loading between 85 and 90 lb/ft^2 (416 and 440 kg/m^2) to give sufficient wing area in the slipstream to ensure satisfactory descent and deceleration capability in transition without incurring wing stall. However, a higher wing loading is desirable for reduced cruise drag, and a loading of 100 lb/ft^2 (489 kg/m^2) was chosen. It has been assumed that methods currently under investigation at Boeing of obtaining satisfactory transition characteristics with high wing loading/disk loading ratios would be perfected by 1980. These methods include programming nacelle tilt relative to wing angle to control angle of attack of the wing in the slipstream, and boundary layer control at the leading edge of the wing to increase the basic wing stall angle. A rotating cylinder could also be applied in this area and might be integrated with the cross shaft.

It is difficult to forecast the improvements to be expected in propeller hover figure of merit and cruise efficiency. Only now are methods being developed that show promise of accurately estimating hover performance of propellers. Therefore, it is still not possible to analytically determine the optimum propeller geometry and operating conditions that give the best compromise between the conflicting requirements of hover and cruise conditions. For this study a hover figure of merit of 0.82 was chosen as representative of the highest value currently believed to be attainable. This figure was combined with cruise efficiencies determined by increasing by 10% the advance ratio at which compressibility effects start to sharply reduce efficiency. This is in line with the projected 10% improvement in critical Mach number for wing sections. The improvement in critical advance ratio was made relative to the cruise efficiency determined for the tilt wing designed in a previous NASA/Boeing V/STOL short haul transport study. The resulting propeller cruise efficiencies are shown in fig. 121.

Propellers on each side rotate down inboard, since it has been shown from Vertol Division wind tunnel tests that this retards stall at the wing root. Because of the placement of the engines on the wing, this rotation of the propeller will not aggravate tip stall.

The shafting that interconnects the engines ordinarily operates in an unloaded condition. However, in the event of engine failure it transmits the remaining power equally to the four propellers. The dead engine is automatically decoupled from the load-carrying shaft by means of an overrunning clutch.

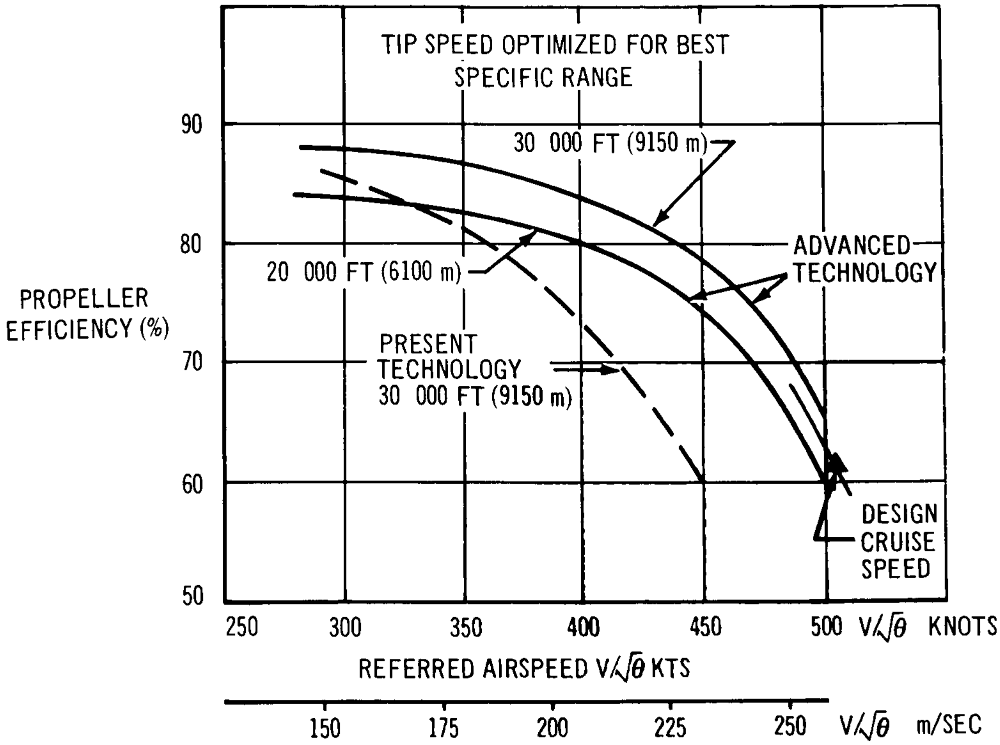


Figure 121: Tilt Wing Propeller Cruise Efficiency

Pitch control in hover is provided by monocyclic (single-axis-cyclic) control propellers. The monocyclic control applied to the rigid propeller blades produces an offset of the thrust from the axis of rotation. Vertol hover tests of monocyclic control have shown that thrust offsets of the order of 27% of the blade radius are readily obtainable at the propeller design lift coefficient.

Monocyclic control alone is capable of providing 80% of the moment required for trim and control under the most severe aircraft CG condition. Additional longitudinal control capability can be obtained, as well as longitudinal acceleration, by linking wing tilt and flap deflection to the stick. This capability is obtained at little or no additional cost, since the high wing rates are readily obtained from the moments generated by monocyclic control and flap deflections. Yaw control in hover is provided by a spoiler deflector control system. As shown by Boeing model tests, the major advantages of this type of control over a differential flap system are that there is little or no depreciation of control power in proximity to the ground and, since no upward flap movement is required, the flap can be optimized for transition performance.

Differential collective pitch, which is used for roll control in hover, can provide roll control up to 2 rad/sec^2 with only minor loss in lifting force. A combination of 50% control about the roll axis and 20% about the other two axes causes a thrust loss of only 3.4%. The most severe hover requirement is therefore that which requires a thrust-to-weight ratio of 1.05 with one engine out on a 89°F day. The engines have been sized for this latter condition. An emergency power rating of 10% above takeoff rating was assumed.

The horizontal tail is an all-movable control surface programmed to wing tilt during transition. Flaps are also programmed to wing tilt during transition.

The wing area has been provided in chord, rather than span, and the wing does not extend beyond the outboard nacelle. This was done to increase span loading and thus improve aircraft gust sensitivity. Gust sensitivity is important for short stage lengths, in which the aircraft will cruise at low altitude and high EAS. This does not significantly affect the drag in high-speed cruise, where induced drag is small.

7.1.2.5.2 Folding tilt rotor: This configuration is a convertible development of the tilt rotor concept. After a normal transition from hover to the forward flight mode, the rotors are feathered and stopped, and the blades are folded rearward into wing tip nacelles. Convertible fan engines, which provide shaft power for the rotor drive system, then convert to give fan thrust for the conventional flight mode. A schematic diagram of the propulsion system is given in fig. 122.

Convertible fan engines in aircraft of this design cruise speed and disc loading generally have a surplus of hover power. It was therefore decided to take advantage of the thrust/power sharing feature of the engines and use diverted fan thrust for pitch and yaw control. Thrust diverting doors close off the fan duct exit in hover and low-speed flight, the doors being actuated automatically at an appropriate wing angle. The thrust is then modulated, by exit louvers and fan blade pitch, proportional to stick and rudder pedal position. Cyclic pitch control could be used but this might compromise the folding mechanism.

The propulsion system of this aircraft dictates virtually all of the major design parameters. The rotor size dictates the minimum span and the sweep angle of the wing, the size of the wingtip pods, and the number and type of engines. The integration of the propulsion and control system dictates the location of the engines and affects the engine airframe matching.

Conversion from rotor to fan propulsion occurs at 160 kn (82.3 mps). This gives an allowable wing loading of 120 lb/ft^2 (587 kg/m^2) for V_{con} = 1.15 (V_S at 0.8 $C_{L_{max}}$) where $C_{L_{max}}$ = 2.3. This wing loading is high enough to give good cruise performance and the $C_{L_{max}}$ value is low enough to be obtained without extremely complex high-lift devices.

A rotor disc loading of 22 lb/ft^2 (107 kg/m^2) is chosen as a compromise between high blade chords and the attendant stowage problem on the one hand, and the large diameters that would require high aspect ratio wings for rotor/fuselage clearance and long tip nacelles for rotor stowage on the other. Wings of high aspect ratio are obviously undesirable from the structural standpoint with this configuration.

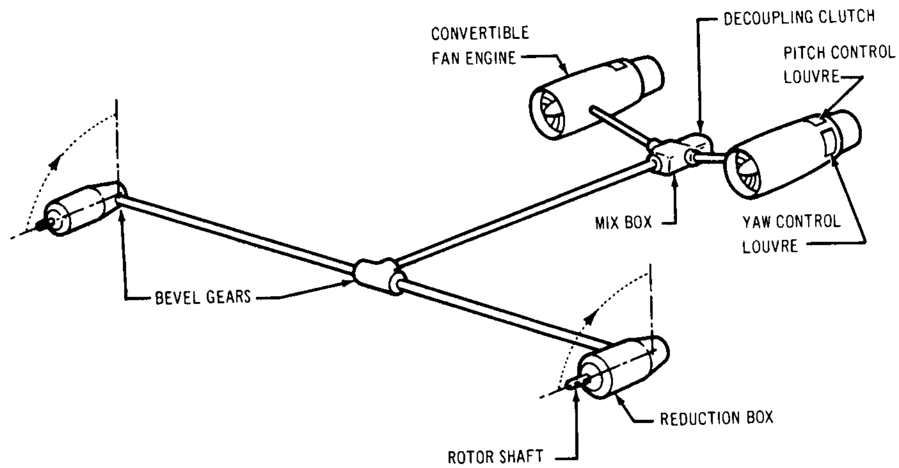


Figure 122: Folding Tilt Rotor Propulsion System Schematic

The hover power required is calculated on the basis of the engine-out control and thrust-to-weight ratio criteria given in the ground rules. Rotor power is calculated using a basic figure of merit of 0.82; a reduction in figure of merit of 0.02 is made to allow for 50% roll control where applicable. The fan thrusts required are converted to combined equivalent power requirements on the basis of the convertible fan engine characteristics given in the propulsion section. This is done for a spectrum of mid-CG positions. The results shown in fig. 123 determine the CG location, relative to the rotor thrust line, for minimum power required.

It was found that a satisfactory hover/cruise match could be attained with two engines for all the folding tilt rotor aircraft. This reduces the overall complexity and maintenance cost and simplifies the hover control system.

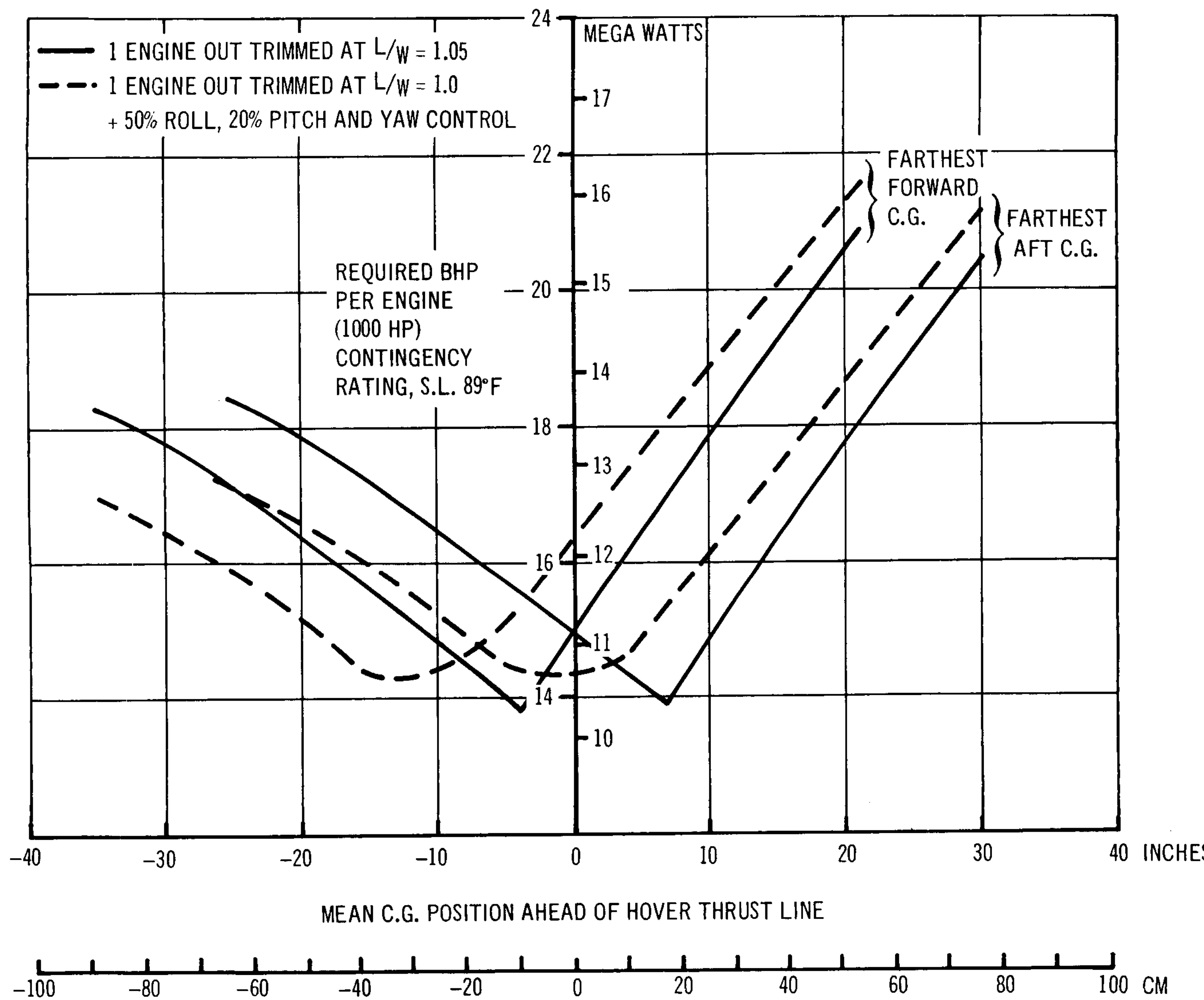


Figure 123: Folding Tilt Rotor VTOL Typical Hover Power— C.G. Optimization

7.1.2.5.3 Stowed rotor: Several concepts of stowed rotor aircraft were considered. Although their economics eliminated them from the route analysis, they are described here for reference.

Single-rotor configurations of both shaft-driven and warm-cycle, gas-driven types were analyzed. It is found that the rotor stowage problem is more severe than that of the tandem configuration. The most serious drawback of the single-rotor type is the large fairing required to house large-diameter blades of adequate chord. The central location of the single rotor indicates the use of the hub retraction for stowage, if adequate airframe clearance is maintained when the rotor is deployed. The alternative is a large central hub body into which the blades retract. Both of these solutions impose severe penalties in weight and complexity on single-rotor configurations. The bulky, high-torque-loading transmission associated with a single, large-diameter, shaft-driven rotor also presents weight and installation problems that are compounded by hub retraction. In addition, a single-rotor aircraft (assuming that the blades are rigid) may experience cyclic pitching and rolling moments as the rotor is stopped for conversion; this is not the case with the synchronized rotors of a tandem configuration.

A shaft-drive, single-stowed-rotor aircraft was considered in a previous study. Two methods of lowering the rotor hub for rotor stowing were considered. These were a retractable transmission and a sliding shaft arrangement. While the latter scheme requires the transmission and shaft to occupy the central portion of the cabin, this was considered to be more acceptable than the extreme complexity of retractable transmissions. The configuration was found to be approximately 15% higher in gross weight than a tandem configuration.

A warm-cycle, gas-driven rotor was also investigated. This aircraft has four lightweight turbofan (bypass ratio 1.6) engines, which supply air for driving the rotor and controlling yaw. Warm-cycle is investigated in preference to hot-cycle because of the reduced noise level with the lower tip jet velocities of the former system. It was found that a blade thickness/chord ratio of 0.21 would be required to obtain sufficient duct cross-section area; and this together with the high hub-to-rotor-diameter ratio would give a low hover figure of merit on the order of 0.5. The high blade thickness would also necessitate a low transition speed and therefore compromise wing design. These factors, together with the complexity of folding blade hinges incorporating gas ducts and the drag penalty of the large hub required for rotor stowage, led to a decision to discontinue study of this configuration.

Rotor stowing on the tandem configuration can be accomplished by lowering the hubs on sliding shafts (with multiple scissor links to transmit torque), folding the blades rearward, and closing the cover doors. The sliding shaft approach is acceptable for a tandem configuration because a very small movement is required to ensure rotor/airframe clearance, and the transmissions can be housed in the vertical fin and in a bay forward of the cabin rather than in the center of the payload space.

The tandem configuration chosen for analysis in the early phases of this study is powered by two convertible turbofan engines. The thrust can be modulated at a constant power turbine speed by the variable pitch fan while shaft power is also provided to drive the rotors. For transition, the fans provide propulsive thrust; at the same time, shaft power is provided for rotor lift.

Conversion to the cruise configuration is accomplished by unloading, decoupling, braking, and stopping the rotors, which are then lowered, folded in the trailing position, and enclosed by retraction of the doors on the fuselage and aft pylon. The droop stops of the rotor blades are centrifugally operated to lock out the flapping hinges when the rotor is stopped for conversion.

Control in the hover and transition modes is obtained in the same manner as for a conventional tandem rotor helicopter, i.e. differential collective pitch for longitudinal control, lateral cyclic for roll control, and differential lateral cyclic for yaw control. The power requirements for these controls are small, and therefore the hover power is dictated by the requirement to hover with one engine failed at a thrust-to-weight ratio of 1.05. In the conventional flight mode, longitudinal, lateral, and directional control are obtained with elevator, ailerons and spoilers, and rudder respectively.

The wing and its high-lift devices have been designed to permit conversion at 140 kn (72 mps) EAS using a 1.15 stall speed criteria; the stall speed is assumed to be at a partial flap setting giving 0.8 $C_{L_{max}}$. This results in a wing loading of 120 lb/ft^2 (587 kg/m^2) for a $C_{L_{max}}$ of 3.0. Since experience with stowed rotor aircraft even in the model form is extremely meager, the possible conversion speed is a matter of conjecture. Most present-day studies assume a speed of around 120 kn (62 mps), which implies lower wing loadings or more sophisticated high-lift devices than those of current turbofan transport aircraft. With the advent of advanced structural techniques such as boron filament composite structures, blade strength and stiffness can be increased, thus permitting higher blade folding speeds without excessive blade weight penalties. It is for this reason that a conversion speed of 140 kn (72 mps) is assumed.

7.1.2.5.4 Helicopter: The helicopter configuration employs the advanced technology rotor outlined in the advanced technology section. Since thrust offset may be required to obtain high performance by unloading the retreating blades and thus avoiding blade stall, a tandem configuration is utilized. The single rotor type cannot take advantage of thrust offset because of the resulting rolling moment, which is, of course, balanced out on the tandem rotor aircraft. The general layout is similar to that of current tandem helicopters. However, it is aerodynamically cleaner than current types, and attention has been paid to reducing interference drag of the nacelle/body and landing gear fairing/body intersections. The fuel is contained in the forward portion of the landing gear fairings to avoid fuel tanks within the body structure or directly attached to it.

Rotor Sizing Procedure: Using the rotor design parameters outlined in the aerodynamics section, $L/D_E = 14.6$ and $C_T/\sigma = 0.261$, a sensitivity study was undertaken to establish cruise altitude, number of engines, and rotor sizes.

Given C_T/σ and tip speed in forward flight, as a result of the forward flight operating point, the total blade area was calculated for a range of gross weights and altitudes. These blade areas were reflected back to a hover tip speed corresponding to a hover C_T/σ of 0.12. This resulted in a hover tip speed of 738 fps (225 mps) corresponding to the blade area required for the cruise altitude of 15 000 ft (4570 m), which was selected on the basis of minimum power required. The rotational tip speed at the cruise condition of 623 fps (190 mps) gives a cruise rpm which is 84% of the hover value. Lower percentages than this would result in rapidly worsening SFC values and a significant reduction in available power.

The cruise powers were then converted to the sea level 89°F emergency power ratings, and the rotor radii required to provide the hover lift presented by the design criteria were determined as a function of the number of engines. Results are shown in fig. 124 for the 60-passenger aircraft. Two engines require rotor radii that give a small but acceptable amount of rotor overlap.

Since the number of engines should be minimized for low maintenance cost and ease of installation, a two-engine configuration was adopted for the 60-passenger aircraft. Similar tradeoffs were made for the aircraft of higher passenger capacities. It was found that the lower installed power-to-weight ratio of these aircraft (occasioned by the improvement in aerodynamic cleanness with increasing aircraft size) necessitated rotors of excessive diameter and unrealistically low solidity with two engines. The 90-, 120-, and 200-passenger aircraft are therefore designed with four engines.

7.1.2.5.5 Jet lift VTOL: Vertical takeoff and landing on the jet lift concept is accomplished with the use of eight auxiliary lift engines plus the deflected thrust of the four cruise engines. These large numbers of engines are used to keep the overall installed thrust and engine-out moments to a minimum, because the control is obtained by differential engine thrust. The lift engines in groups of four are located at the ends of the passenger compartment.

The wing is optimized for cruise with secondary considerations of conventional landing and transition speeds. The sweep is 30°, the aspect ratio is 7, and the wing loading is 160 to 170 lb/ft^2 (780 to 830 kg/m^2) as determined by fuel volume requirements. A triple-slotted flap similar to that on the CTOL is used.

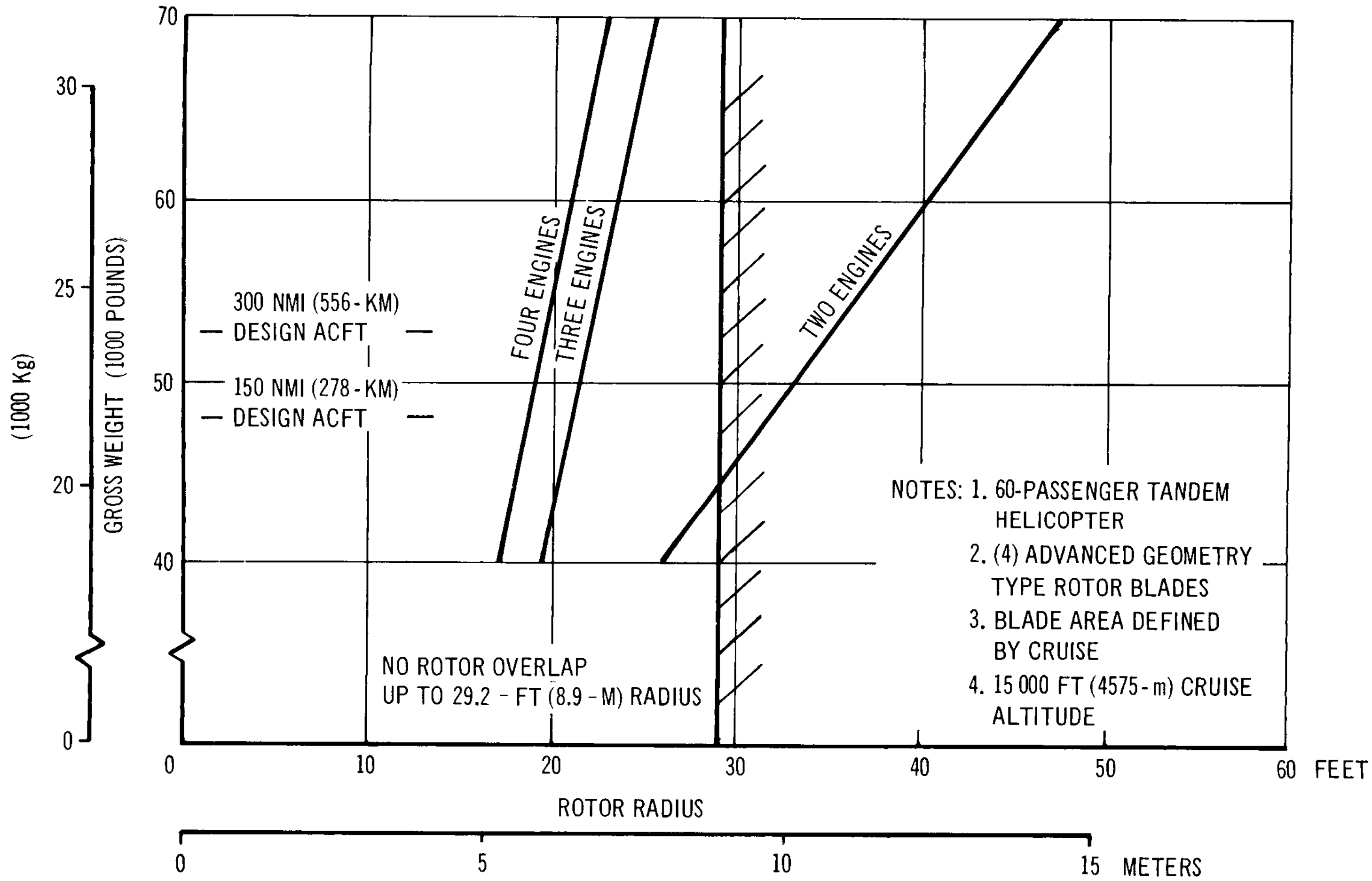


Figure 124: Effect of Number of Engines on Rotor Radius

7.1.2.5.6 Fan-in-wing VTOL: The fan-in-wing has four lift fans set in the inboard sections of the wing, two on each side. The main torque box for the wing passes between the fans. Two fan-in-wing concepts were considered, one with tip-driven fans and one with concentric fan engines. In the tip-driven fan configuration, four gas generators housed in a fairing over the fuselage center section supply the driving air for the lift fans. With each gas generator connected to two opposing fans, the loss of one gas generator reduces the thrust on two fans to 63% of maximum.

In the concentric fan concept, the gas generator is integral to the fan and requires no hot gas ducting. This concentric fan shows approximately 5% reduction in DOC over the tip-driven fan.

Both versions of the fan-in-wing use tip-driven fans for roll, yaw, and pitch control. The gas generators necessary to drive the tip-driven control fans are located in the fuselage aft of the cabin.

For additional vertical thrust, the thrust from the two cruise engines is deflected downward as in the jet lift concept.

By 1985, the compact design of fan and integral concentric gas generator can be faired into the wing root.

To simplify the installation of these lift fans, a highly tapered low-aspect-ratio wing with a relatively low wing loading is used. To keep the trailing edge of the wing from being swept forward, wing sweep is set at 35°. A simple flap with $C_{L_{max}} = 2.0$ is used.

7.1.2.5.7 High-lift STOL: The high-lift STOL uses an externally blown flap that allows an approach lift coefficient of approximately 4.0 (usable $C_{L_{max}} = 6.7$). For the downtown STOL, a wing loading of 60 is used, and for the suburb a wing loading of 90. Both configurations have a high wing with an aspect ratio of 8.5.

The aft portion of the trailing edge flap will articulate with throttle movement. At high power settings, as for a go-around, the aft flap will be deflected only 50° to 60°, but with reduced power (down to the throttle gate at approximately 65% power) the aft flaps will deflect as much as 90° or more to allow for steep STOL approaches.

With the external blown flap feature, a four-engine configuration is most desirable. With one engine out, the blowing air from the remaining engine spreads out and covers most of the area behind the dead engine, so that the engine-out roll and drag increments are much smaller than would be expected.

In this concept, as in the high acceleration STOL, the stall speed margin on approach is no longer an adequate method of analysis. In this study, maneuver margins have been used allowing for 0.44 g under an all-engine operating case, and 0.33 g with one engine out.

7.1.2.5.8 High-acceleration STOL: STOL performance on this concept is accomplished by the addition of vectoring lift engines to an otherwise conventional airplane. These lift engines supply additional horizontal thrust and are primarily used for deceleration and acceleration but do provide some additional lift. The reduction in approach speed is not more than 30%. In fact, conventional aerodynamic flight controls are all that are provided with this concept.

The wing loading, sweep, and aspect ratio are similar to the CTOL. The flap is somewhat more exotic, however, being a full-span, triple-slotted flap with a $C_{L_{max}}$ (FAA) of 4.7.

Because of the additional horizontal thrust of the lift engines, the loss of a cruise engine on takeoff is not critical. Therefore, a two-cruise-engine configuration is used with engines sized for cruise. The four lift engines are mounted longitudinally beneath the cabin floor just in front of and just behind the wing box. The lift engines are sized by the landing field length required.

7.1.2.5.9 CTOL: The conventional airplane follows closely the design philosophy of current short-range aircraft. Incorporating the flap technology improvements predicted for 1985 allows a wing loading of 105 lb/ft^2 (514 kg/m^2) without increasing the approach speed above 124 kn (64 mps). The wing sweep and aspect ratio are typical of current small jets and are continued here as a good compromise between takeoff requirements and cruise Mach number. A two-engine configuration is used here to minimize cost.

7.1.2.6 Gust alleviation. — Weight estimates of all the concepts in this study are based on a maneuver-critical limit load factor of 2.5, with allowance for a gust load factor of 2.65 at lighter weights. When a 7% elastic relief factor is allowed for, three of the VTOL concepts have design gust load factors within this limit. The tilt wing, CTOL, and high-acceleration STOL, however, will require gust alleviation of as much as 20% to 25%. And, in the case of the high-lift STOL, the amount of gust alleviation available will dictate the design cruise speed at low altitude. For the purposes of this study, the high-lift STOL is limited to the 20% to 25% gust alleviation of the CTOL.

Any substantial gust alleviation requires more than normal flight control surfaces. One method relies on rapid actuation of the wing flaps (deflected upwards as well as down). It is considered feasible that development of acceleration sensors placed in the airplane structure would allow enough lead time for the gust alleviation devices to reduce the gust load on the airplane by 50% or more of the unalleviated value. The major problems blocking a workable system today lie in stabilizing an elastic airplane with a gust alleviation system operational; expanding the flight regime over which the gust alleviation system is 50% to 75% efficient; and providing sufficient fail-safe redundancy in the system to allow certification, as a maneuver-critical airplane, of one that would be gust critical if unalleviated.

Another desirable system, because of the low-altitude, high-speed flight regime of these aircraft, is modal suppression, which can be used in conjunction with gust alleviation or separately to reduce the number of structural cycles the airplane goes through in response to a single gust. The modal suppression system uses acceleration sensors in the airframe and works through a stability augmentation system to operate the control surfaces of the aircraft to damp out unwanted oscillations.

7.1.2.7 Noise level comparisons. — Estimates of the perceived noise levels of various concepts are presented in figs. 125 through 136. The results are based on the methods presented in sec. 7.1.1.3. To convert these PNdB values to community noise rating, add the appropriate increment from table 10. The takeoff and landing profiles on which these noise levels are based are shown in figs. 137 through 139. Figures 126 through 129 show the takeoff (landing similar) noise contours at ground level of the four VTOL concepts for a 300-ft vertical rise followed by a climbout angle of 20°. The noise contour at the level of a tall building (300 ft or 91.5m) for this same takeoff profile is shown in fig. 130 for the jet lift airplane.

The effect of varying the vertical climb altitude is shown in fig. 131, again for the jet lift airplane. Lesser climbout angles tended to draw out the 90-PNdB contour along the flight path as shown in fig. 132.

For the STOL concepts, climbing turns after takeoff were considered in an attempt to contain the noise in the vicinity of the terminal. For the high-acceleration STOL, it was found that running the lift engines at partial power (25%) to allow a climbout angle of 20° is preferable from a noise standpoint. The comparison of a straight climbout with a turning climbout is made on fig. 133 for this climb angle. Figure 134 shows both 6° and 12° approach noise profiles with a takeoff level for reference. Although 20° climbouts

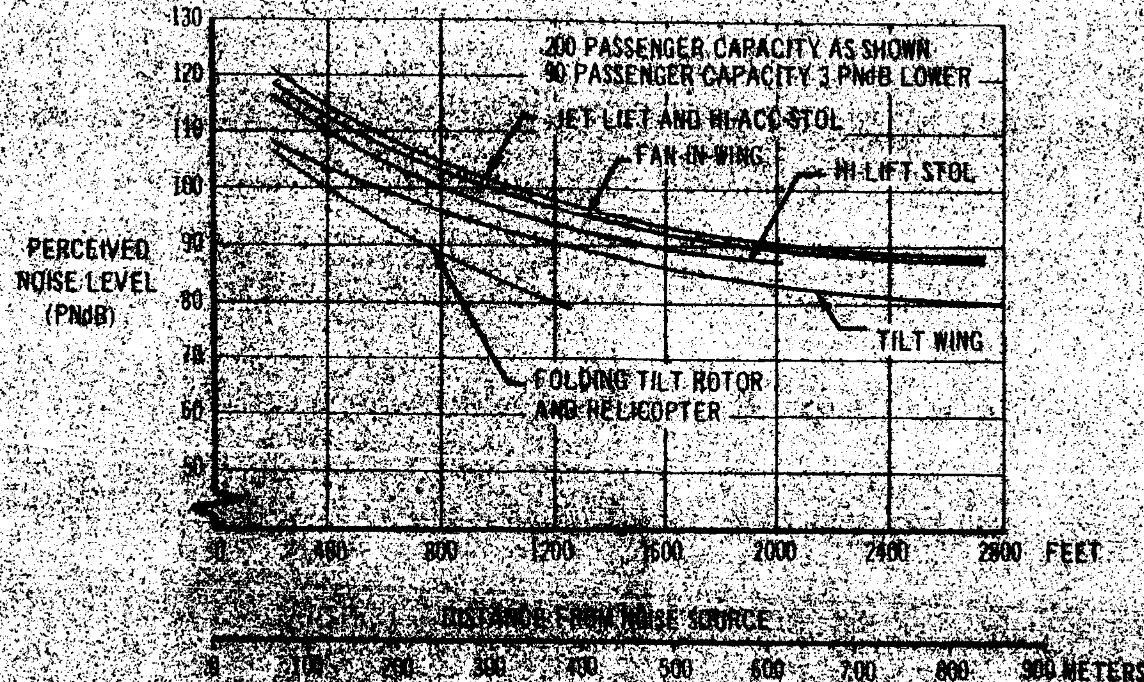


Figure [illegible]: Perceived Noise Levels – Concept Comparison

Table 10: Increment for Conversion from Perceived Noise Level (PNL) to Community Noise Rating (CNR)

Type of Aircraft	PNL to CNR Conversion			
	Large City		Small City	
	Complex	Pad	Complex	Pad
VTOL	10	5	5	0
STOL	10	–	5	–
CTOL	10	–	5	–

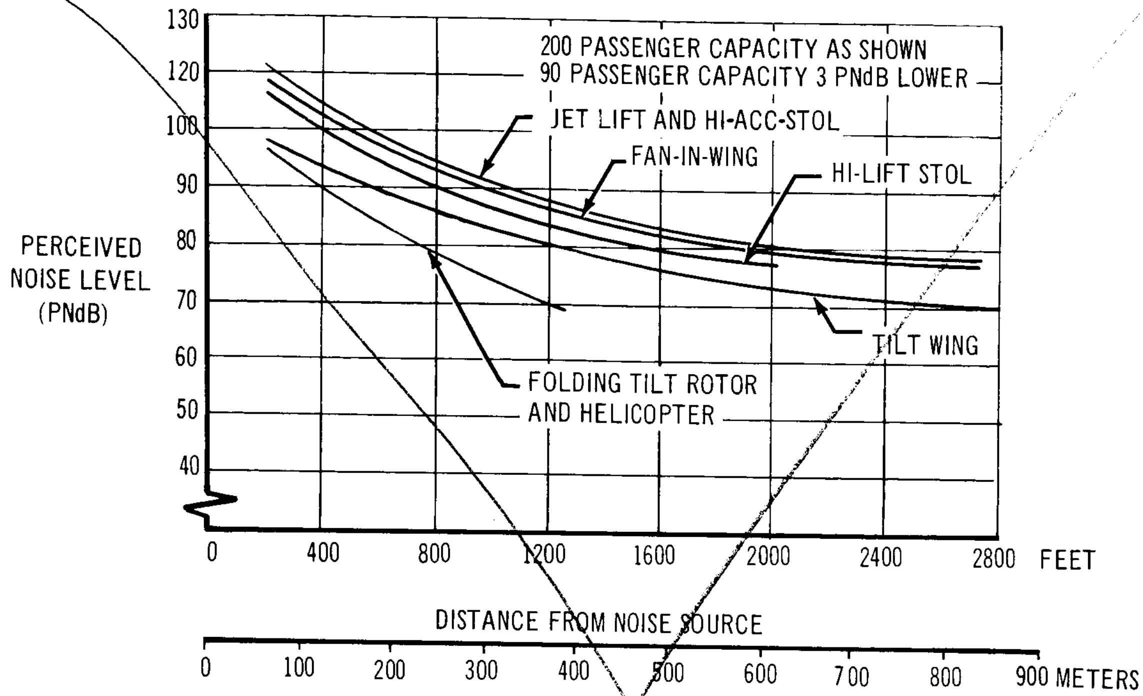


Figure 125: Perceived Noise Levels – Concept Comparison

Table 10: Increment for Conversion from Perceived Noise Level (PNL) to Community Noise Rating (CNR)

Type of Aircraft	PNL to CNR Conversion			
	Large City		Small City	
	Complex	Pad	Complex	Pad
VTOL	10	5	5	0
STOL	10	-	5	-
CTOL	10	-	5	-

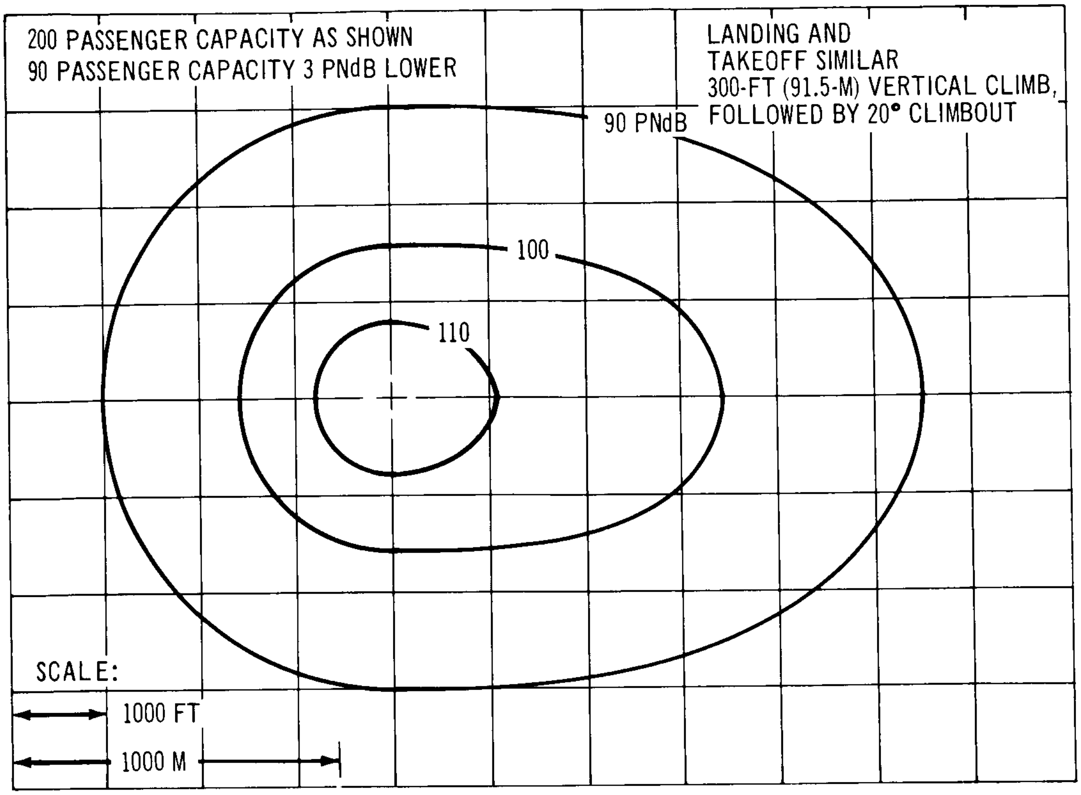


Figure 126: Noise Contours—Jet Lift VTOL

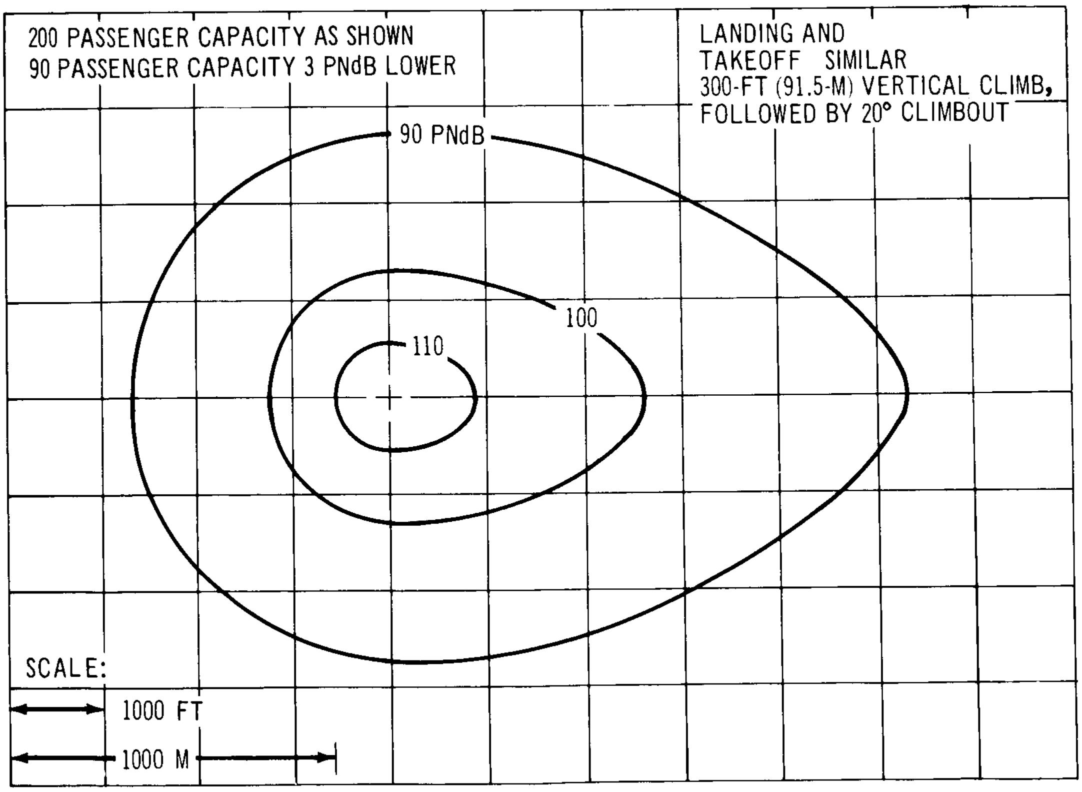


Figure 127: Noise Contours—Fan-in-Wing VTOL

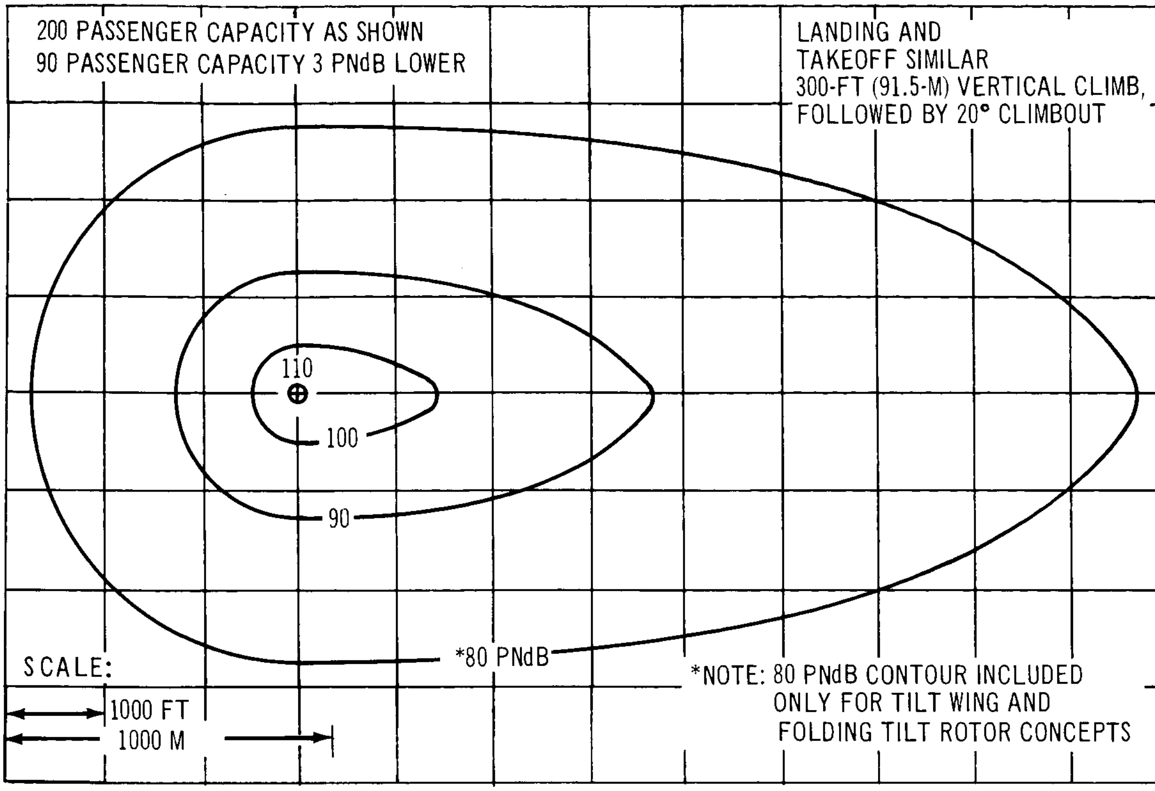


Figure 128: Noise Contours—Tilt Wing **VTOL**

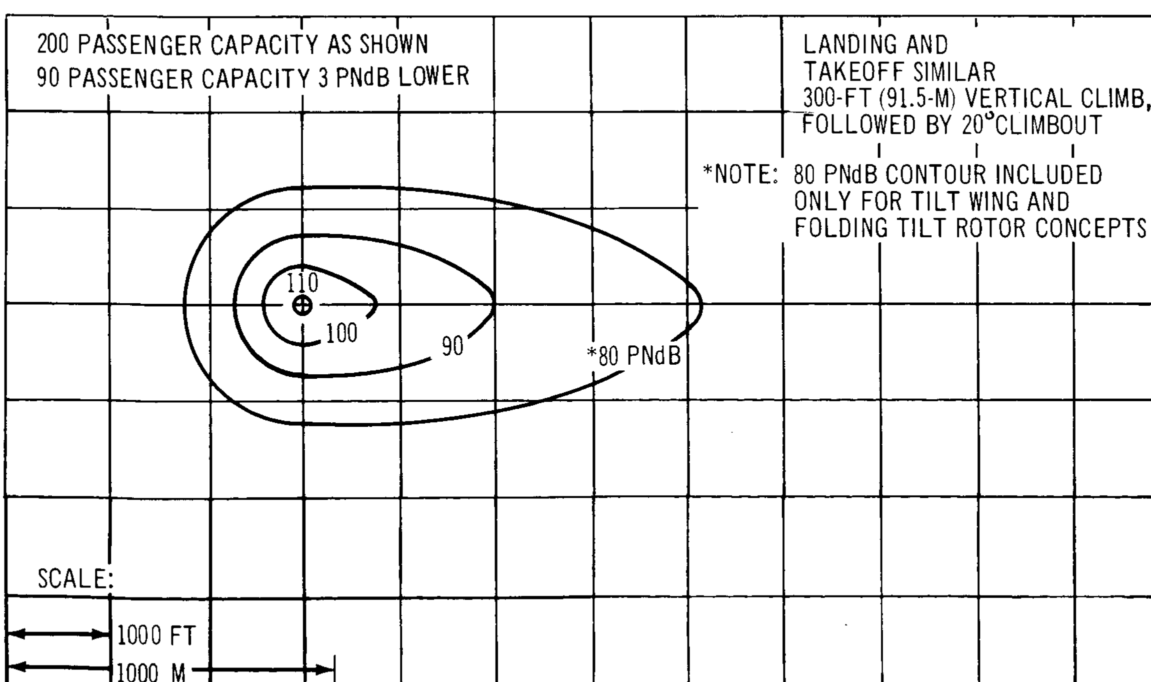


Figure 129: Noise Contours—Folding Tilt Rotor **VTOL**

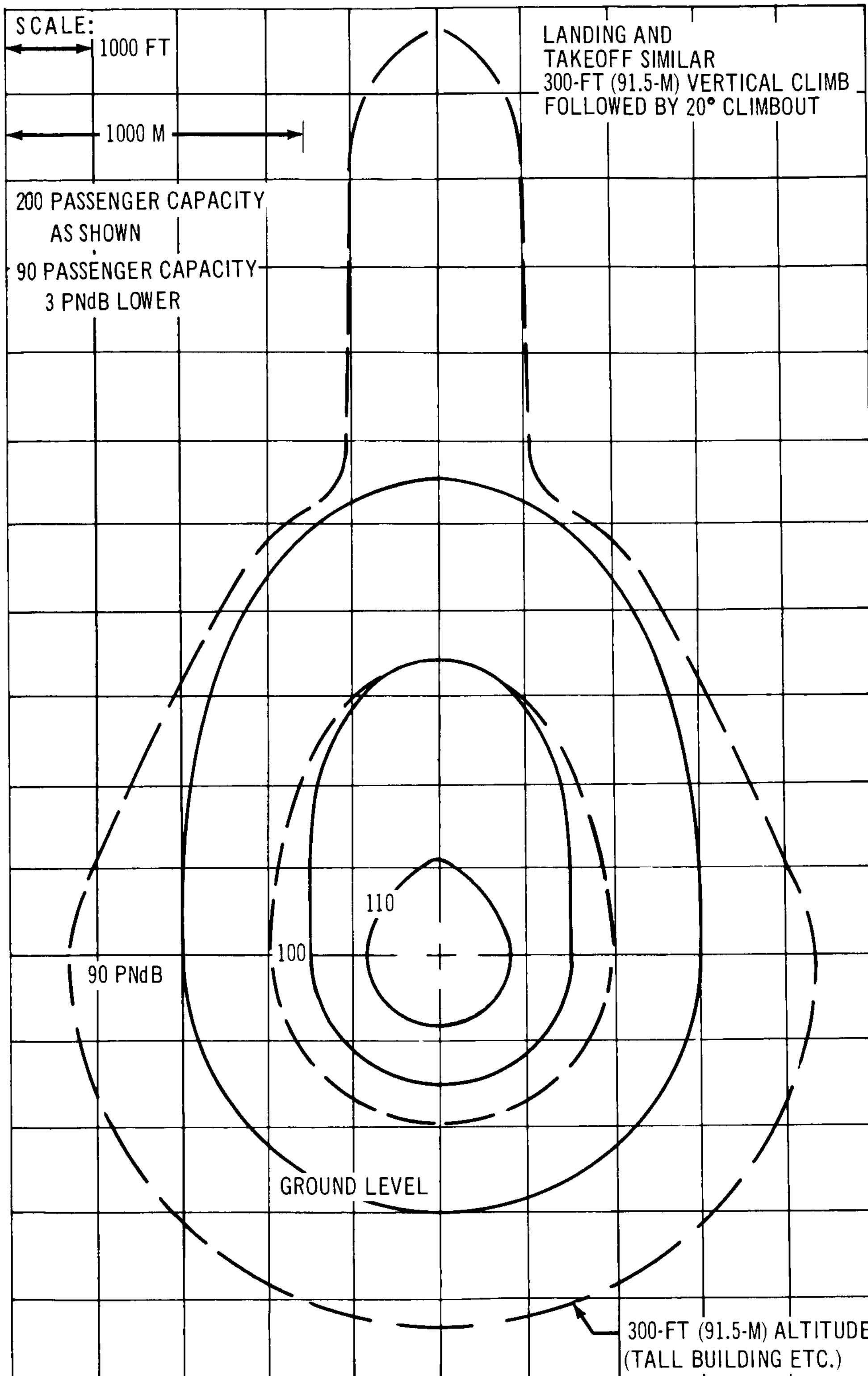


Figure 130: Noise Contours for Tall Buildings—Jet Lift VTOL

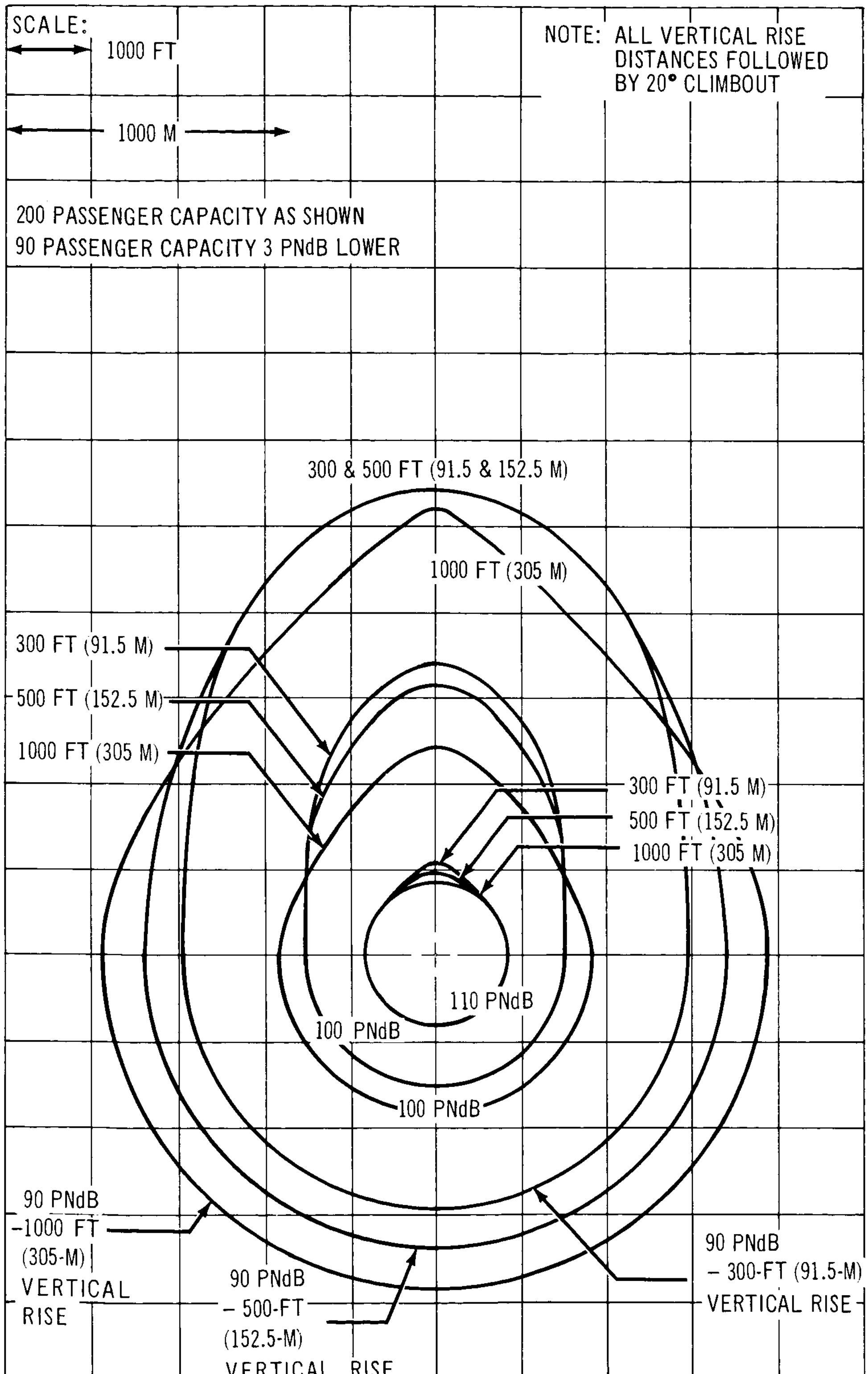


Figure 131: Effect of Vertical Rise Distance on Noise Contours—Jet Lift VTOL

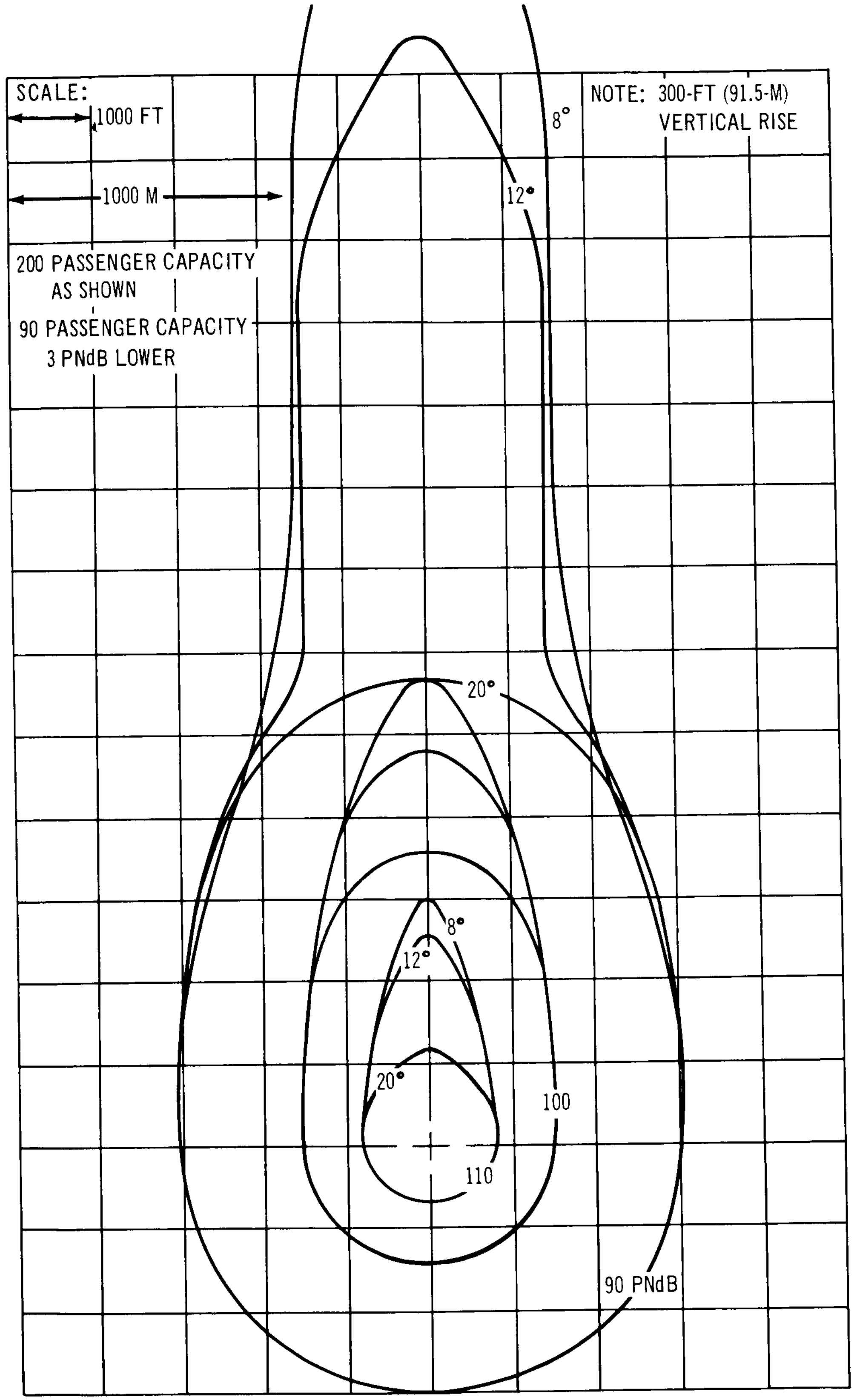


Figure 132: Effect of Climbout Angle on Noise Contours—Jet Lift VTOL

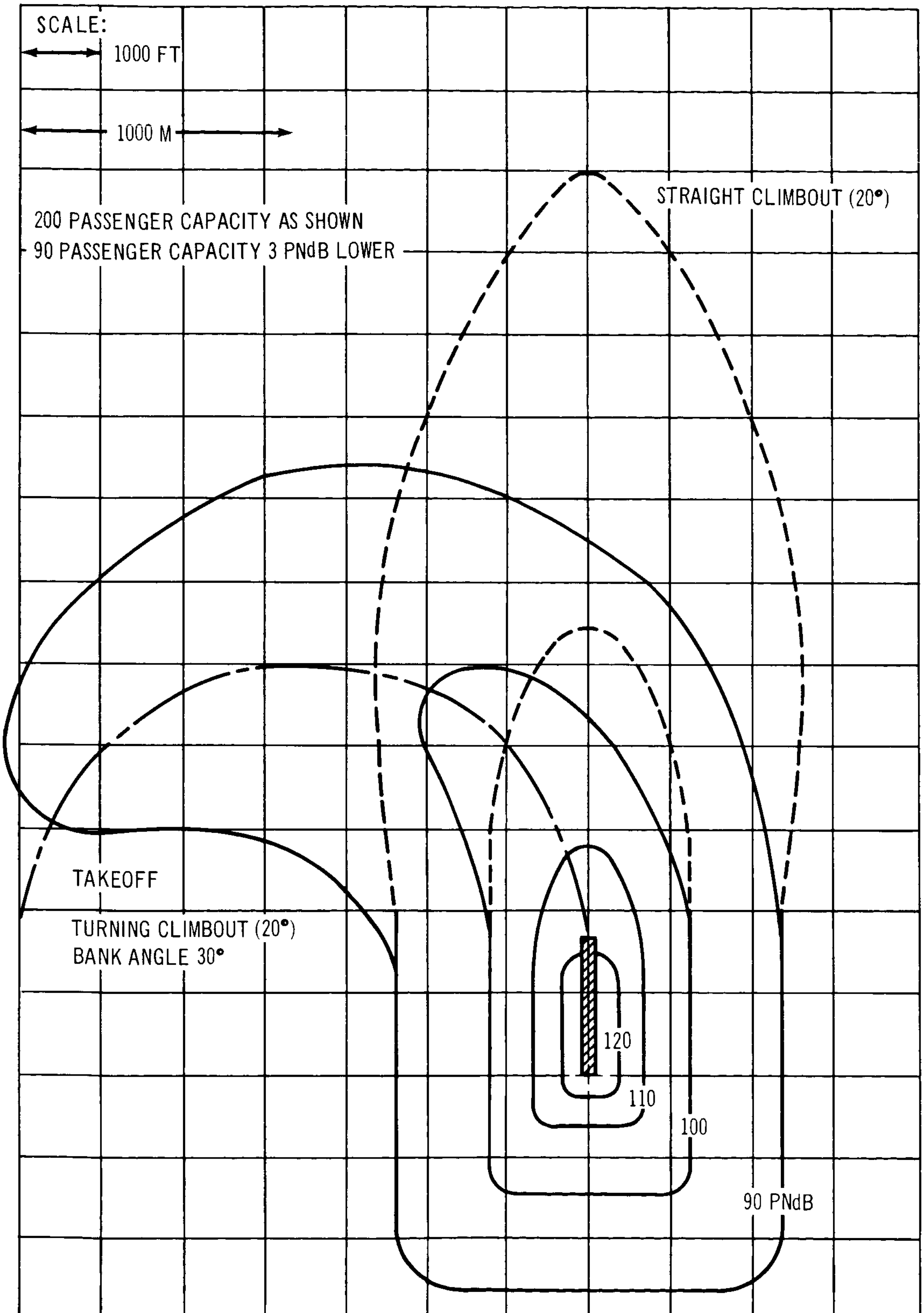


Figure 133: Noise Contours—High-Acceleration STOL, Different Takeoff Procedures

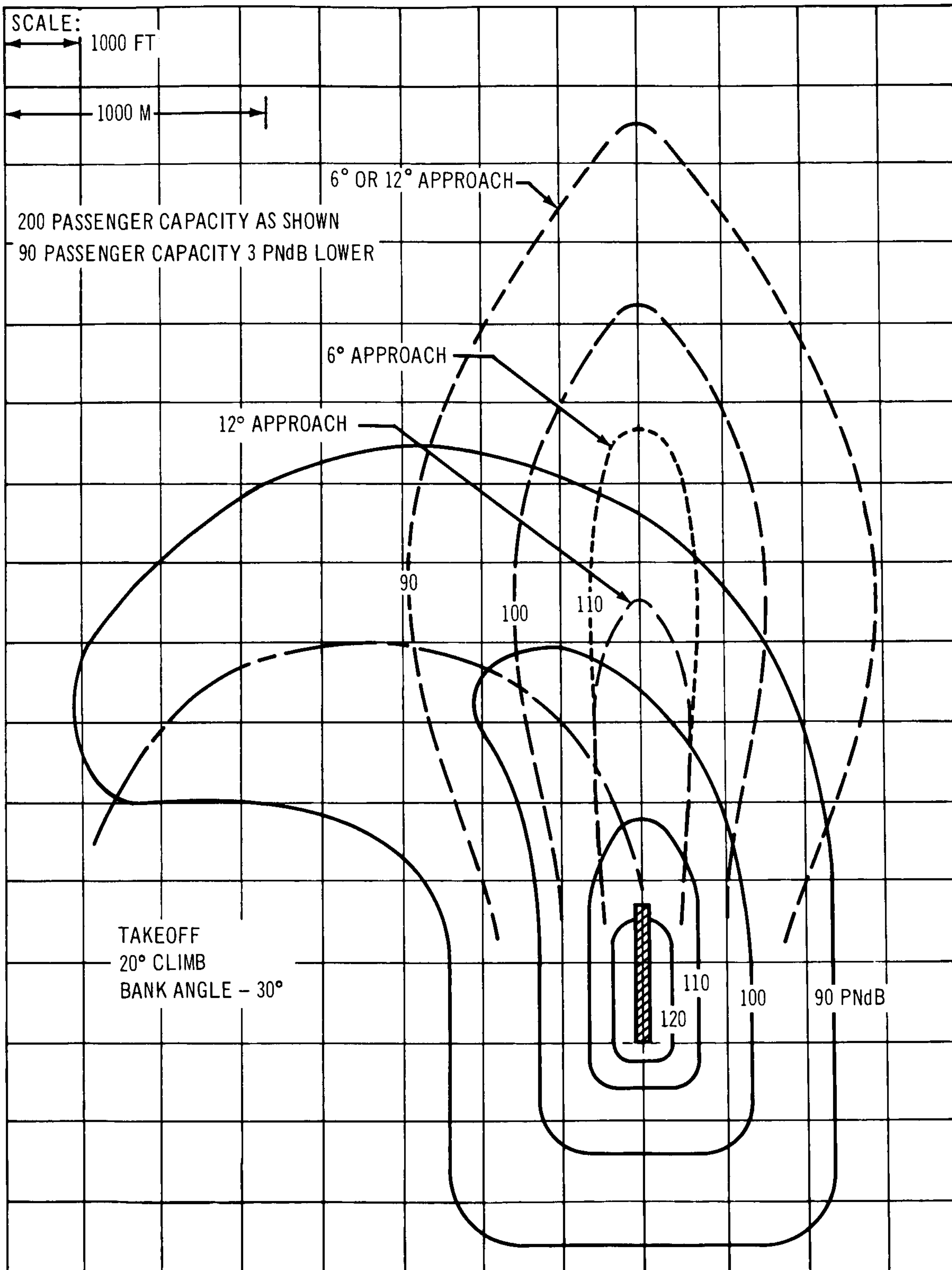


Figure 134: Noise Contours—High-Acceleration STOL, Comparison of Takeoff and Landing

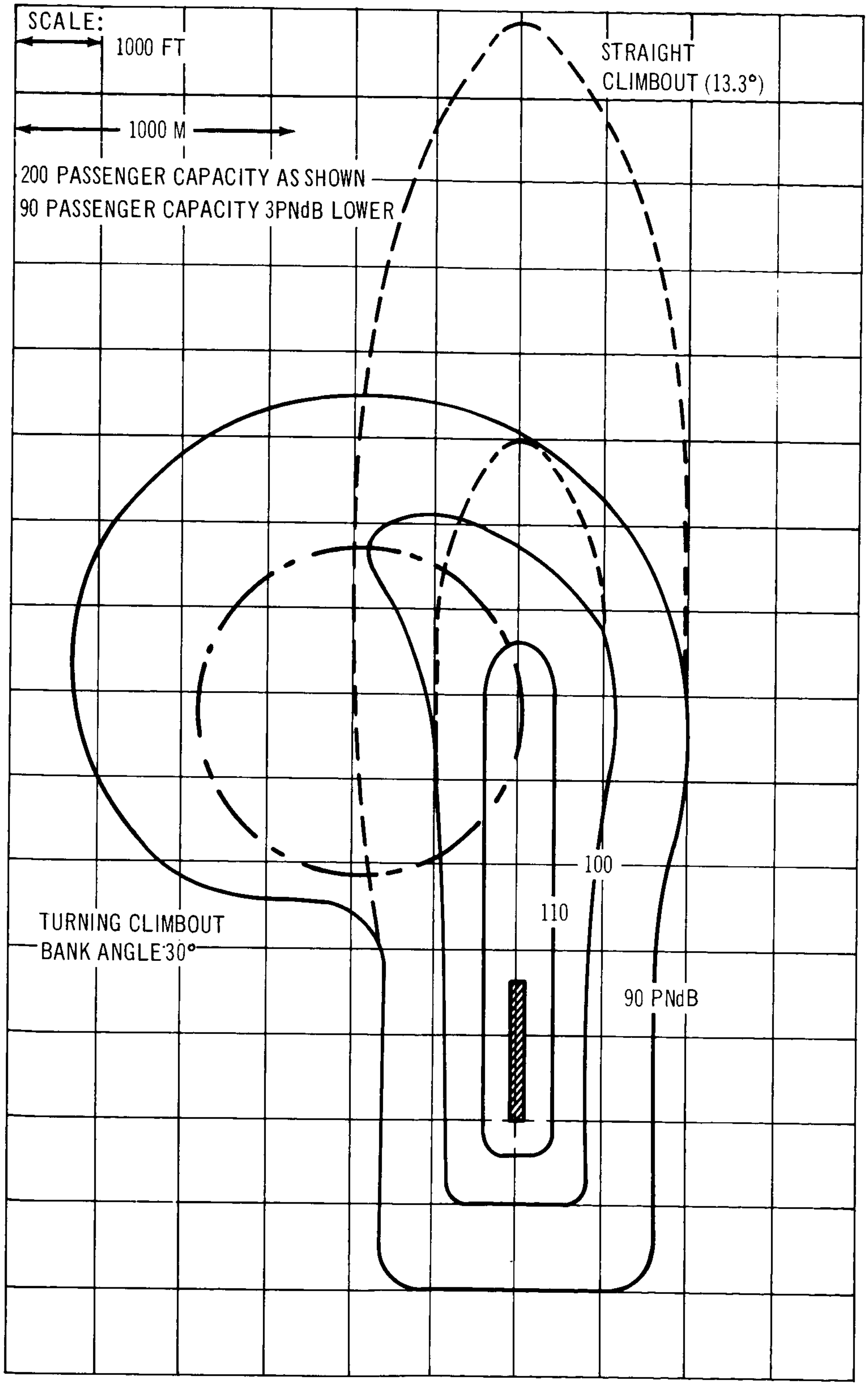


Figure 135: Noise Contours—High-Lift STOL, Different Takeoff Procedures

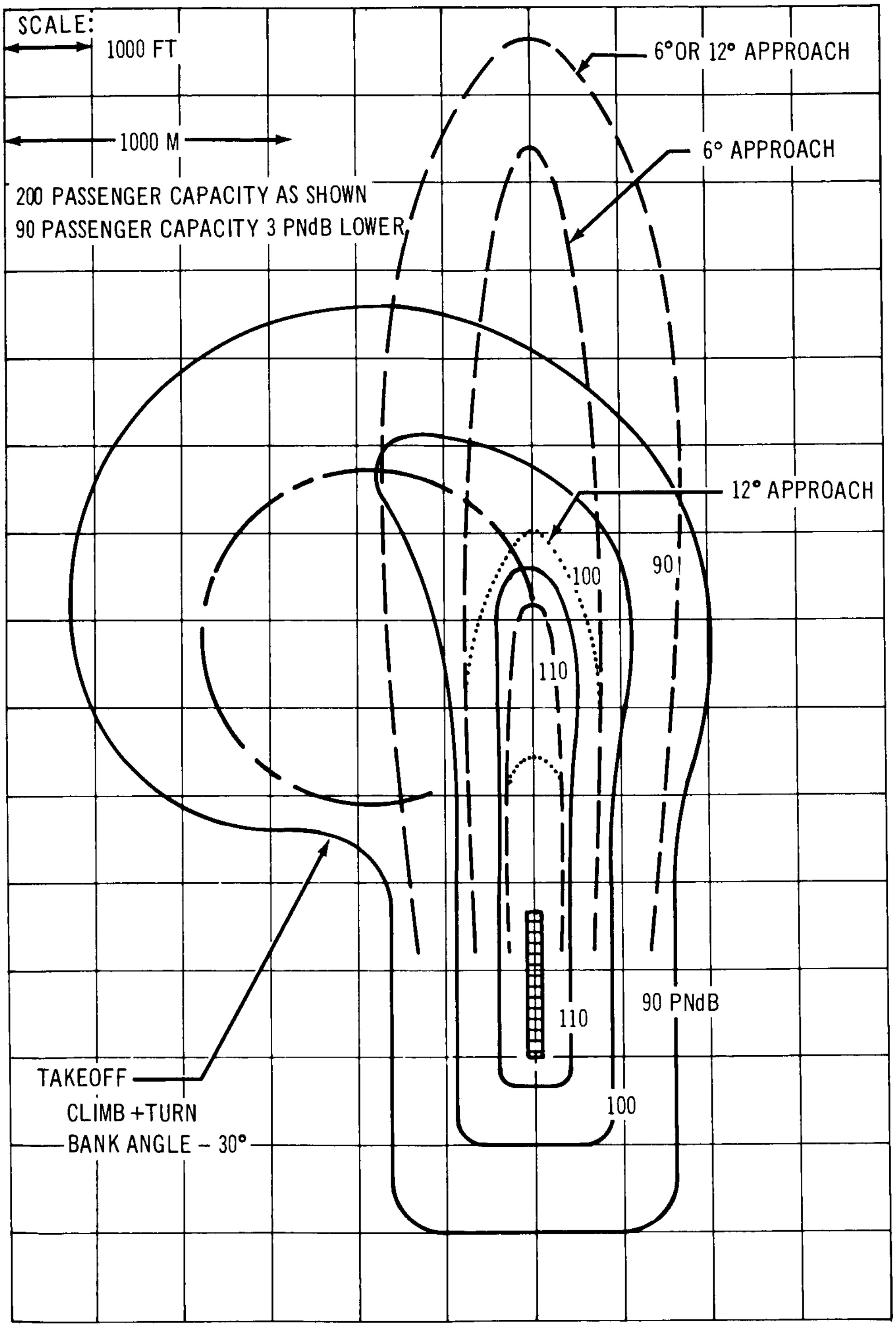


Figure 136: Noise Contours—High-Lift STOL, Comparison of Takeoff and Landing

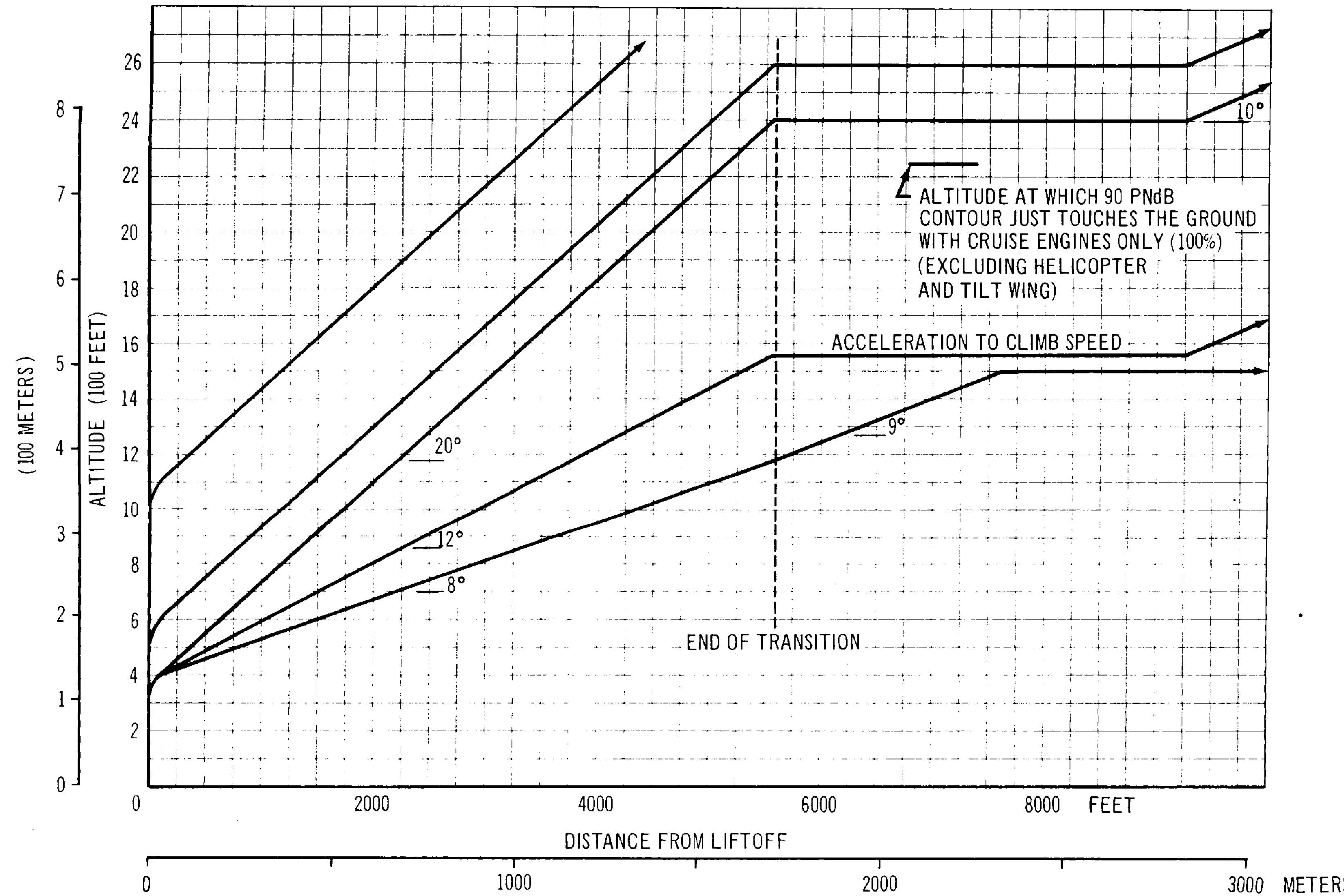


Figure 137: Takeoff Profile VTOL

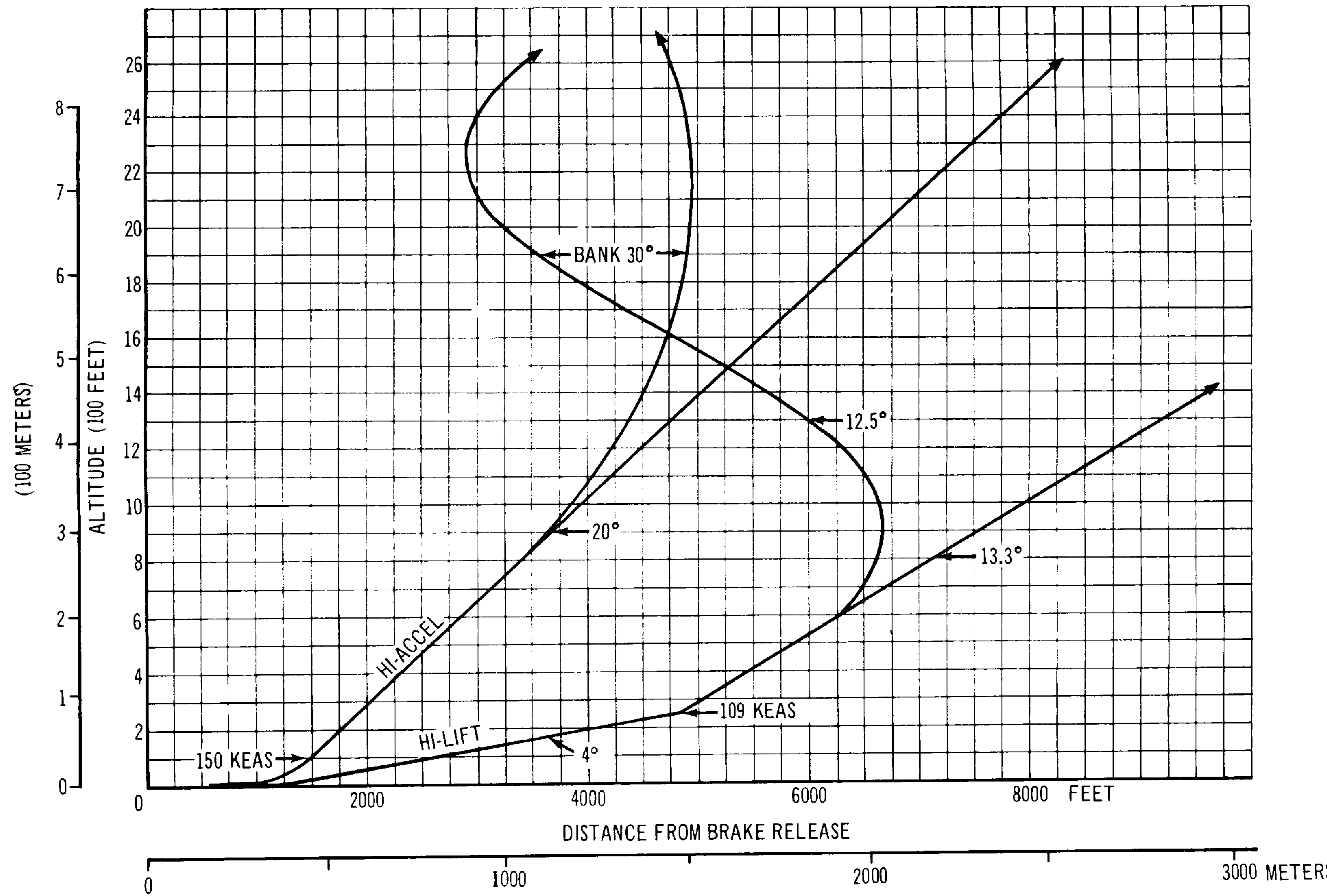


Figure 138: Takeoff Profile STOL

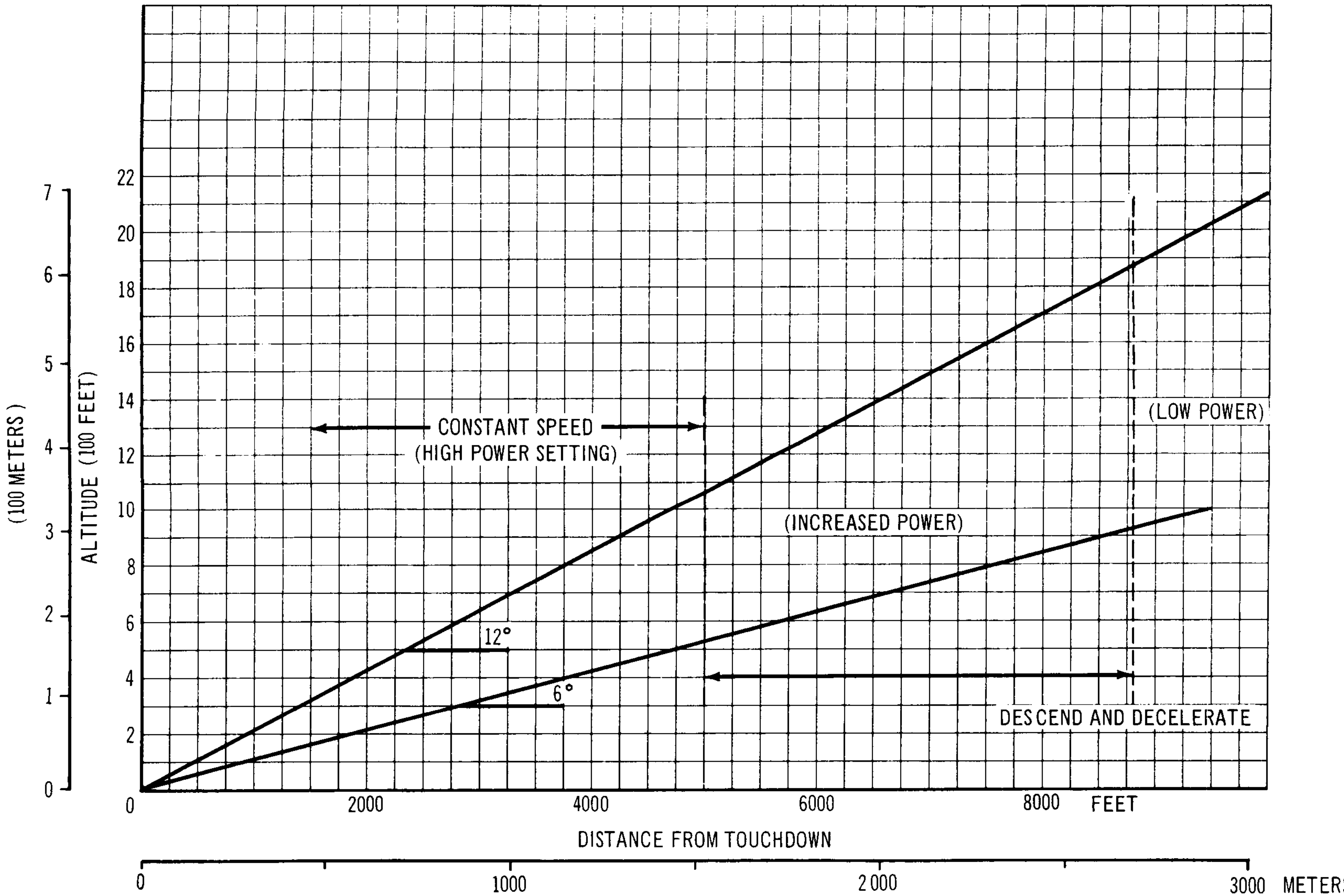


Figure 139: Approach Profile STOL

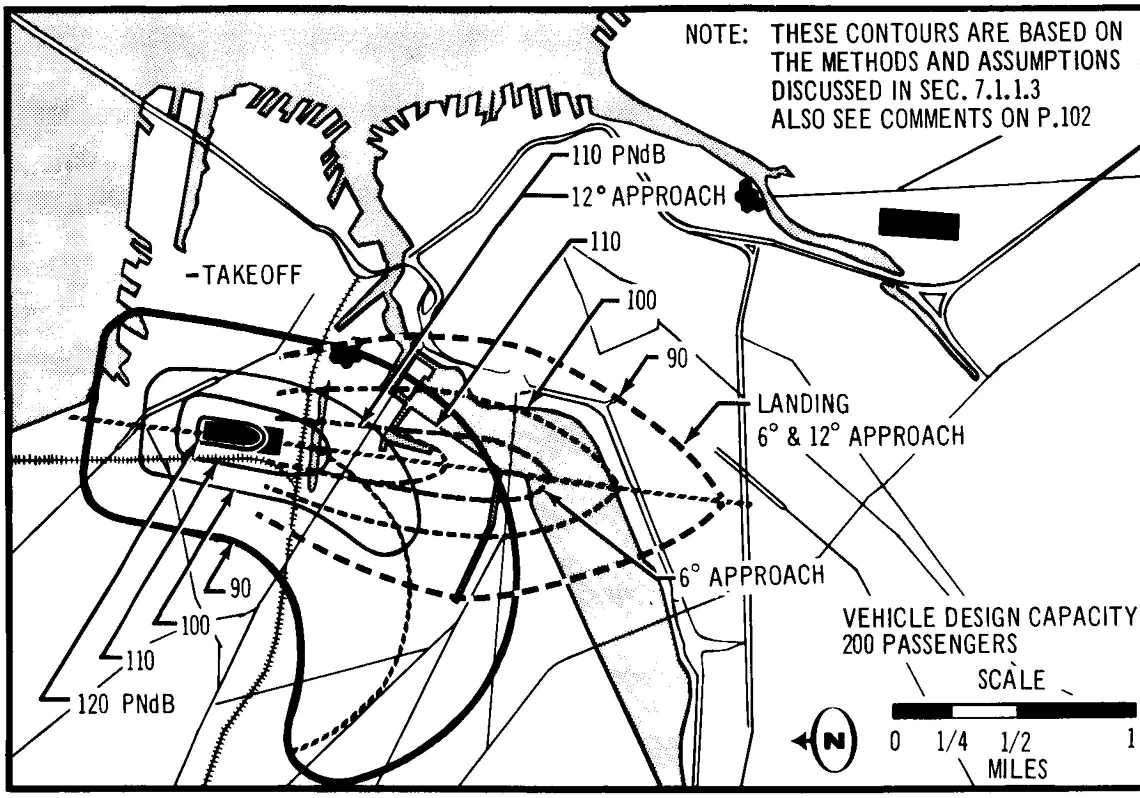


Figure 140: High-Acceleration STOL Noise Contours—Boston

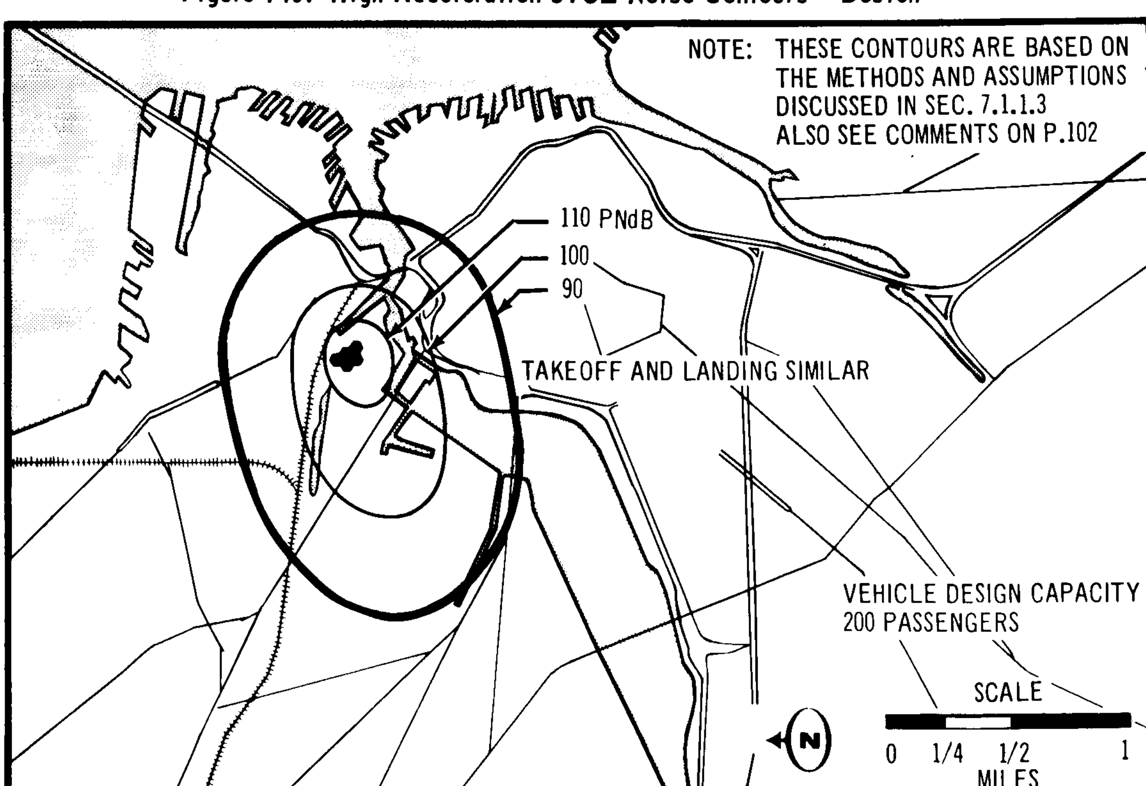


Figure 141: Jet-Lift VTOL Noise Contour—Boston

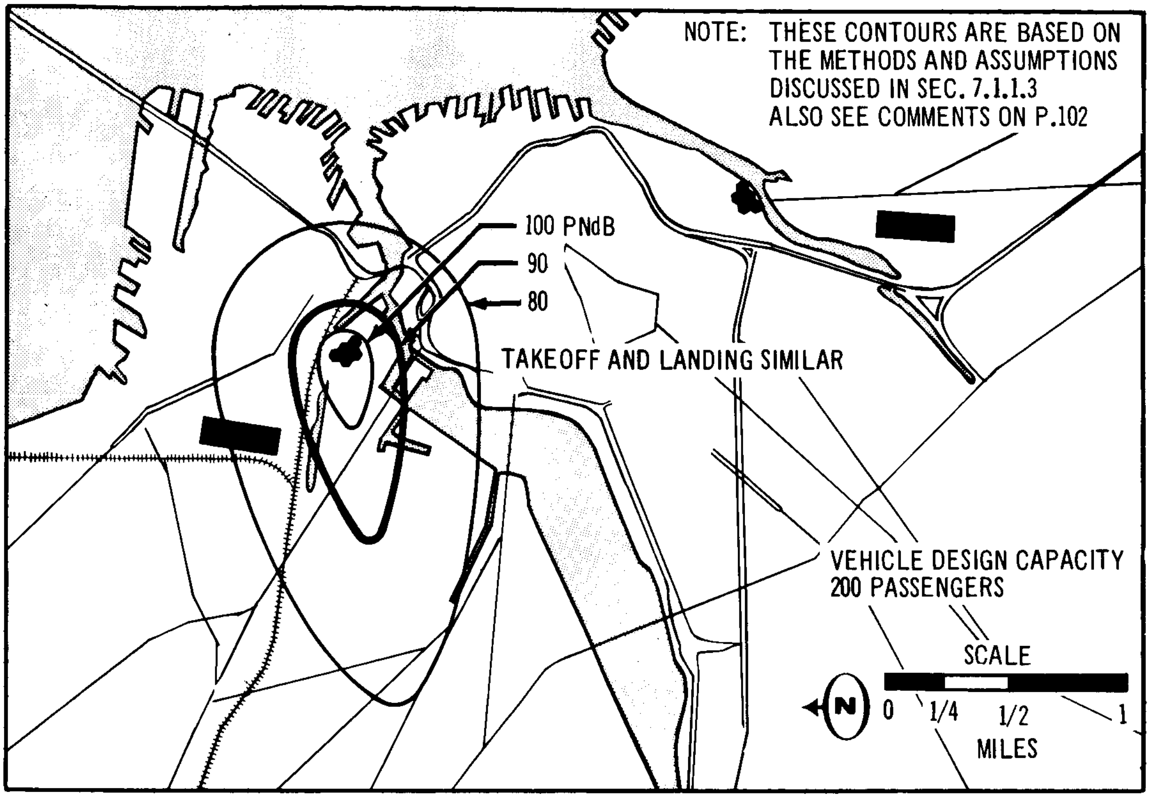


Figure 142: Tilt-Wing VTOL Noise Contour—Boston

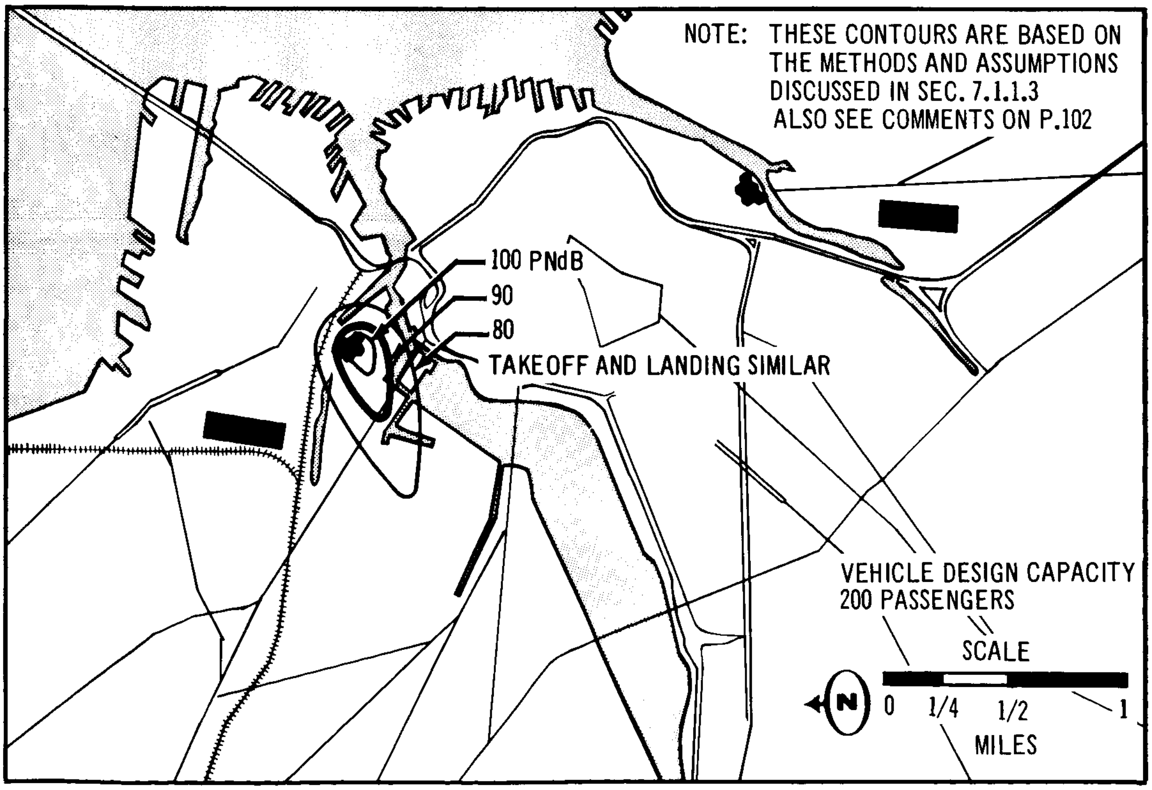


Figure 143: Folding Tilt Rotor VTOL Noise Contour—Boston

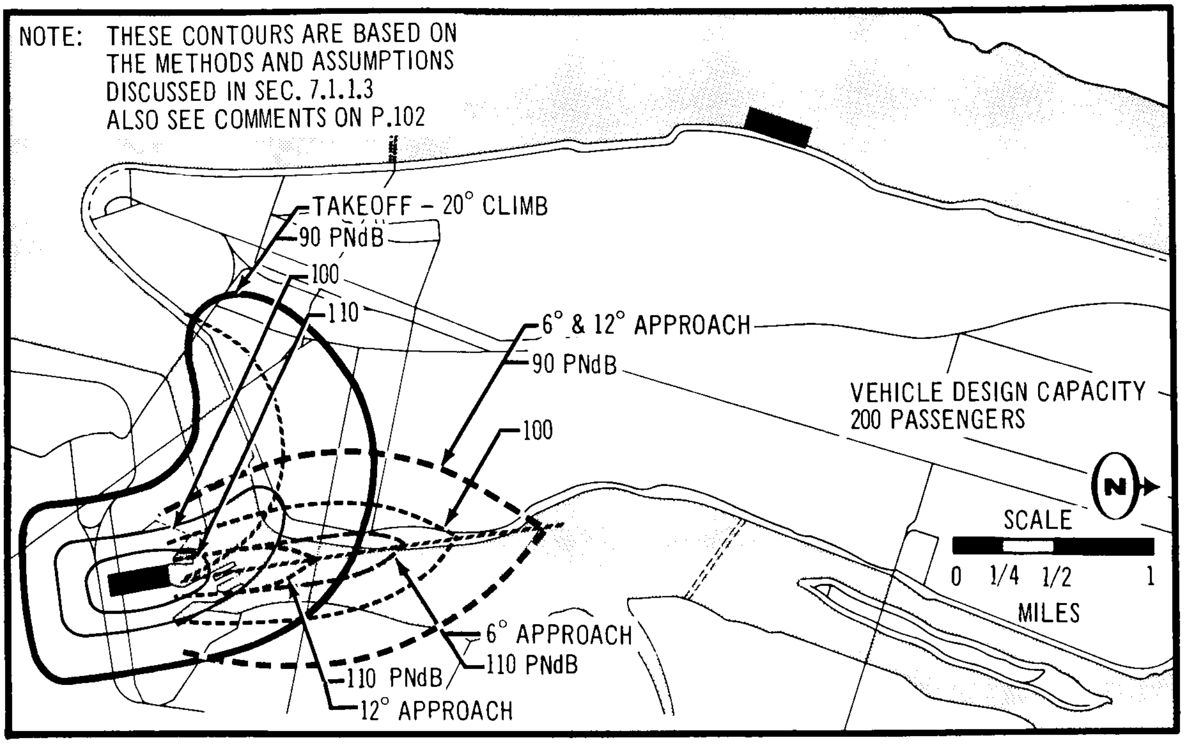


Figure 144: High-Acceleration STOL Noise Contours—New York

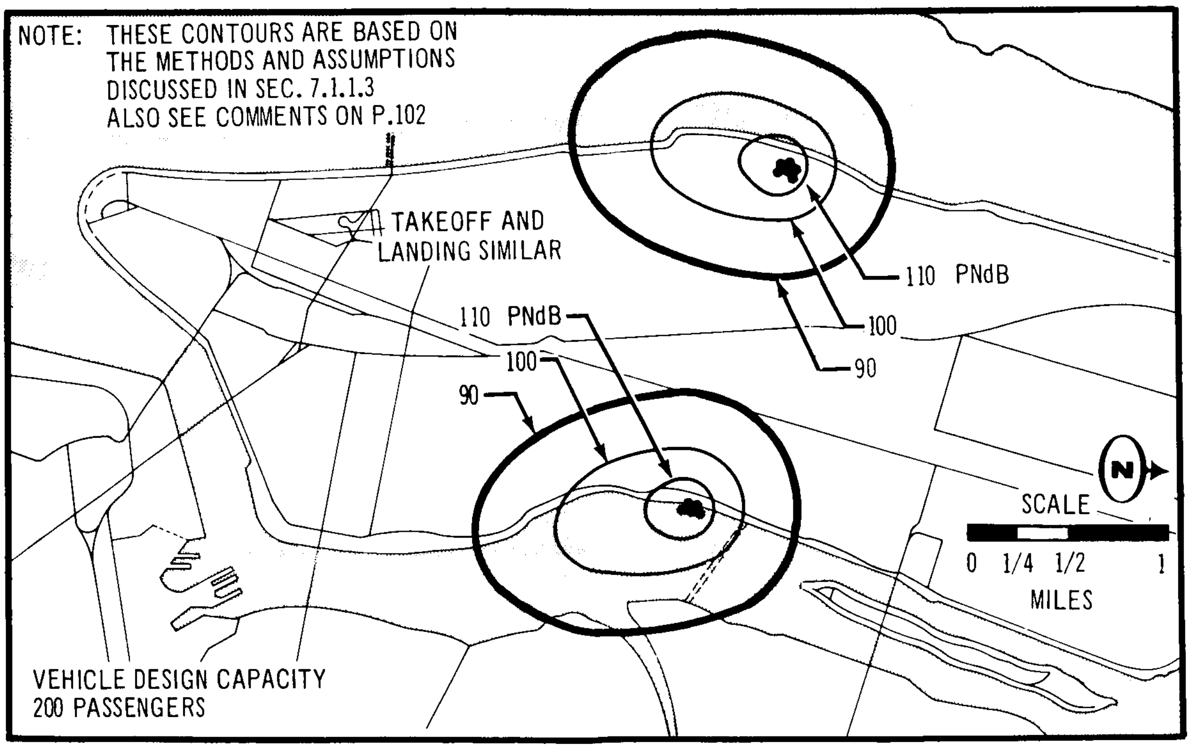


Figure 145: Jet-Lift VTOL Noise Contours—New York

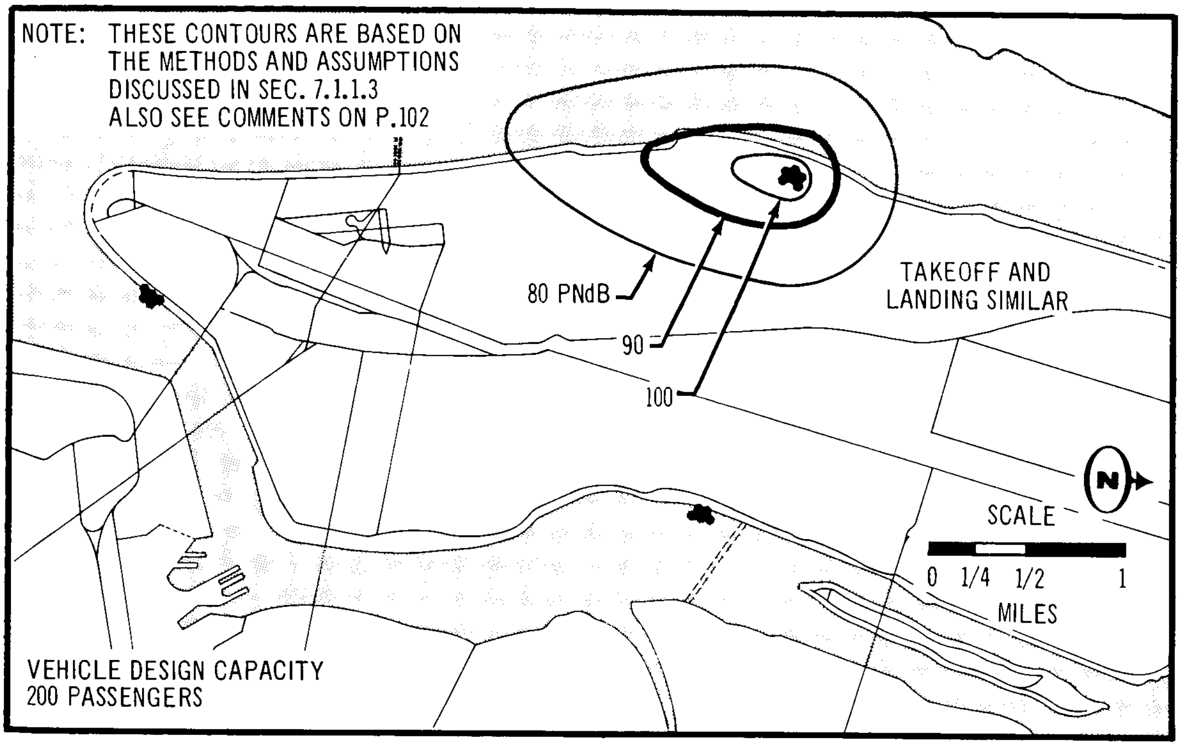


Figure 146: Tilt-Wing VTOL Noise Contours—New York

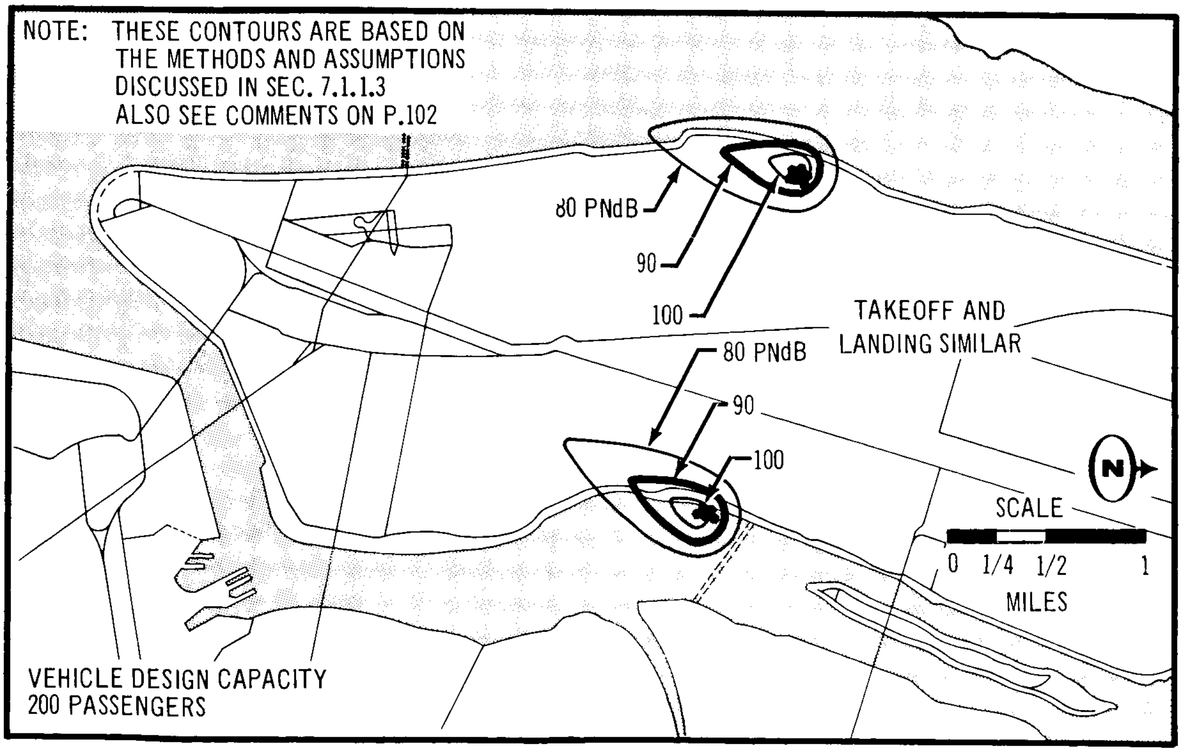


Figure 147: Folding Tilt Rotor VTOL Noise Contours—New York

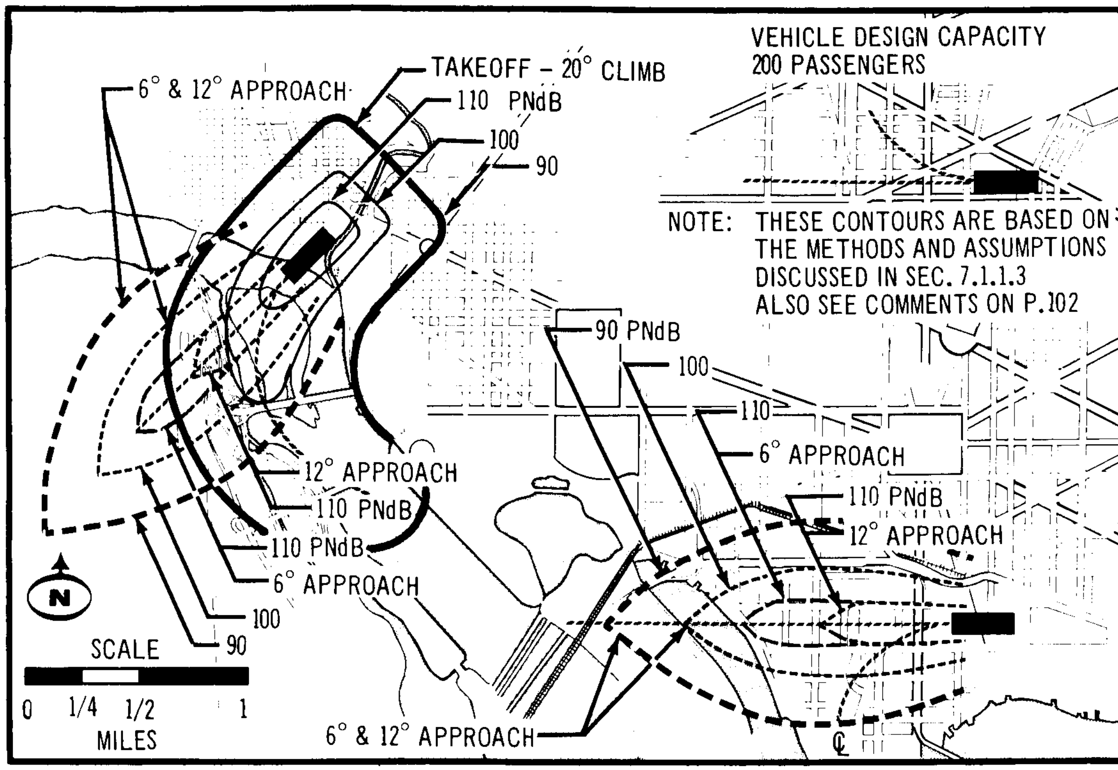


Figure 148: High-Acceleration STOL Noise Contours—Washington, D.C.

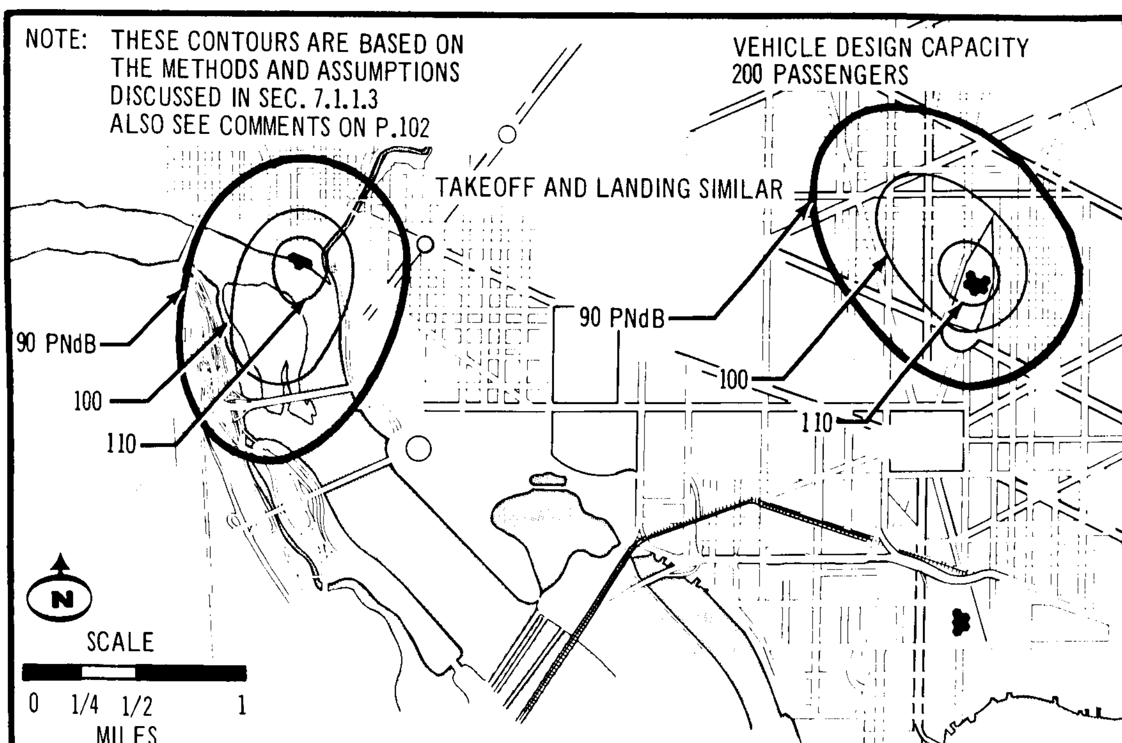


Figure 149: Jet-Lift VTOL Noise Contours—Washington, D.C.

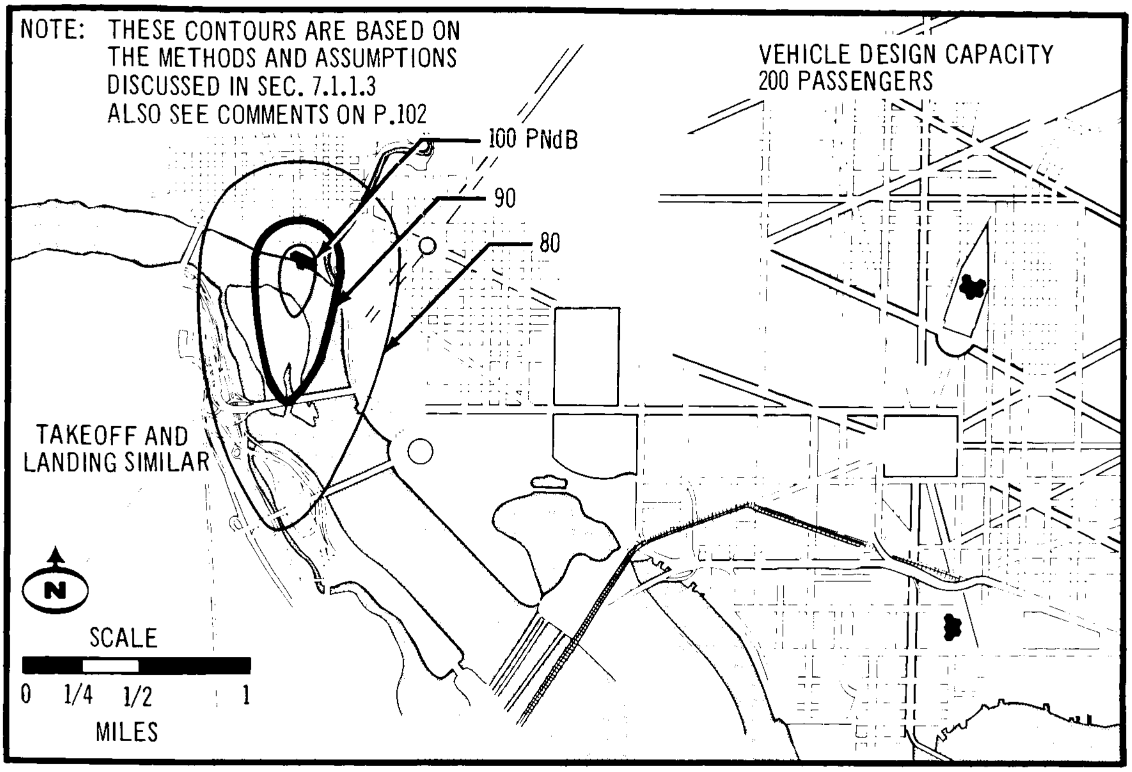


Figure 150: Tilt-Wing VTOL Noise Contours—Washington, D.C.

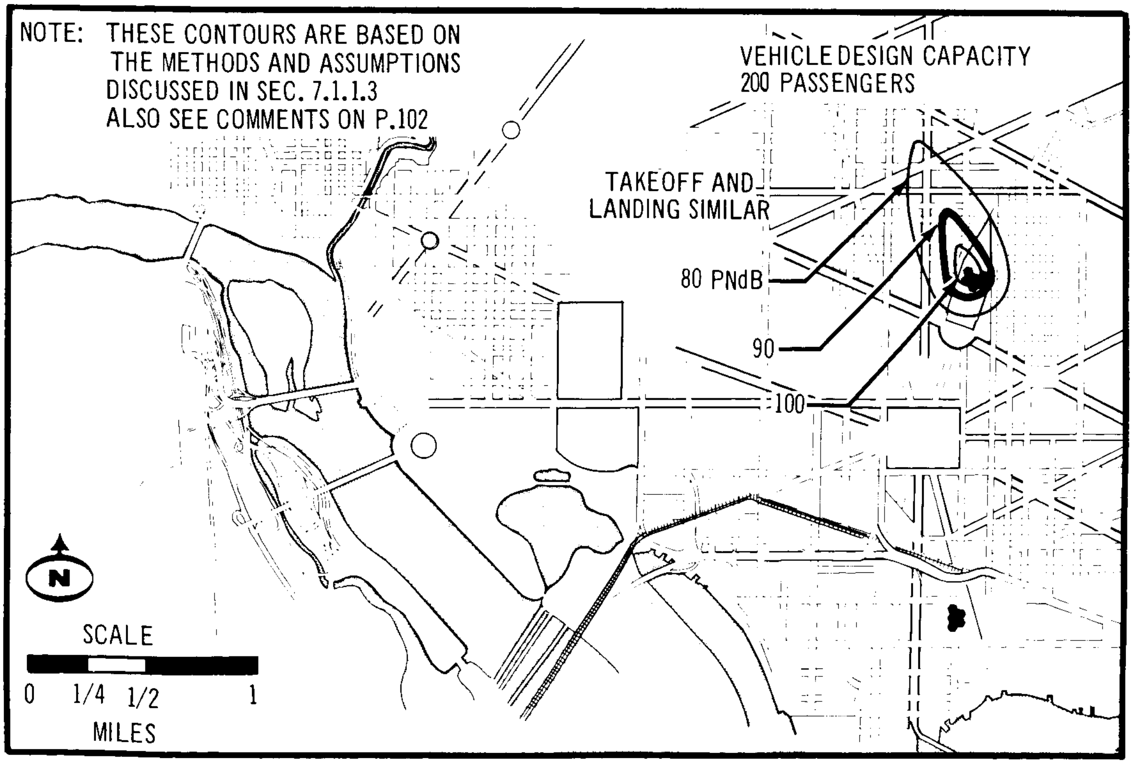


Figure 151: Folding Tilt Rotor VTOL Noise Contours—Washington, D.C.

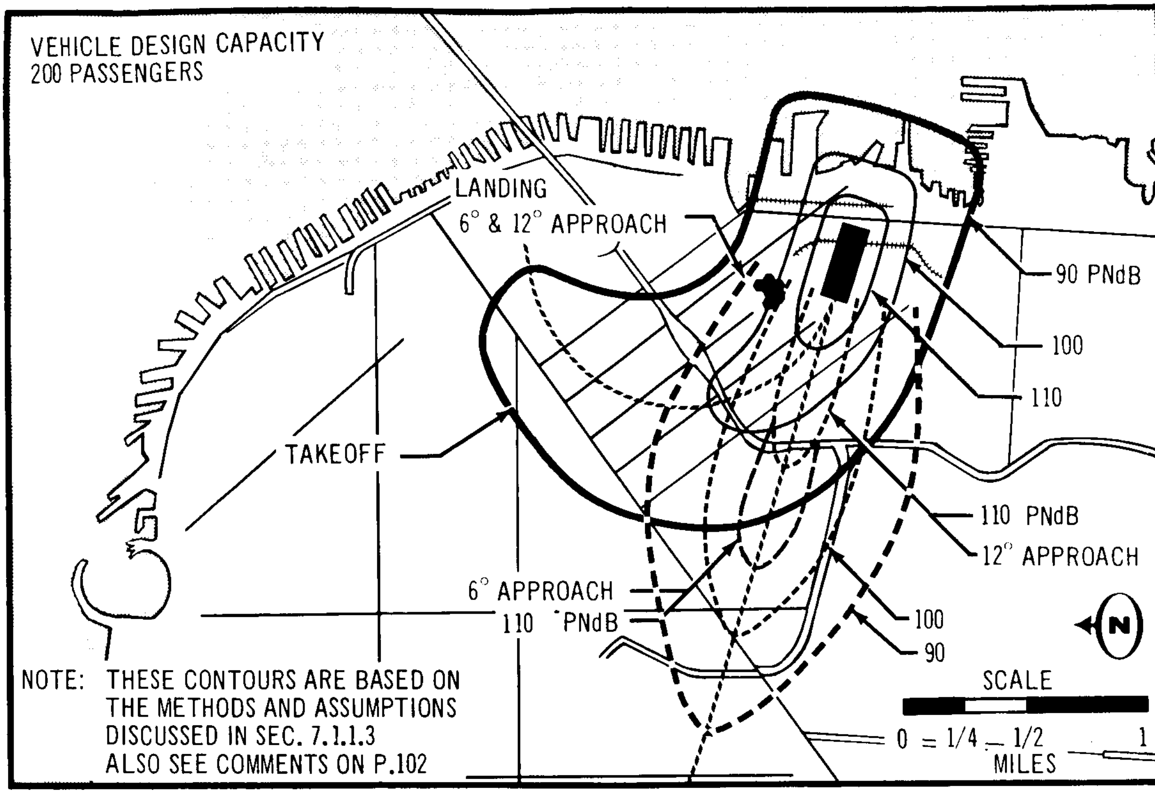


Figure 152: High-Acceleration STOL Noise Contours—San Francisco

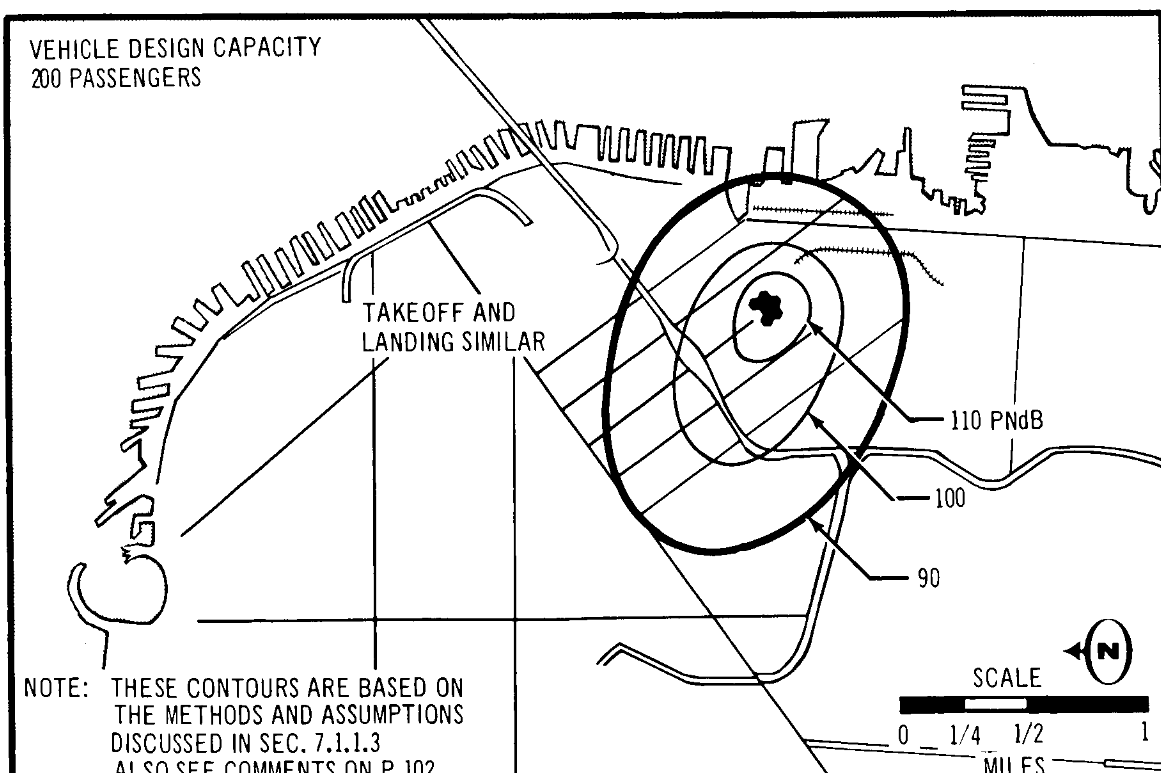


Figure 153: Jet-Lift VTOL Noise Contours—San Francisco

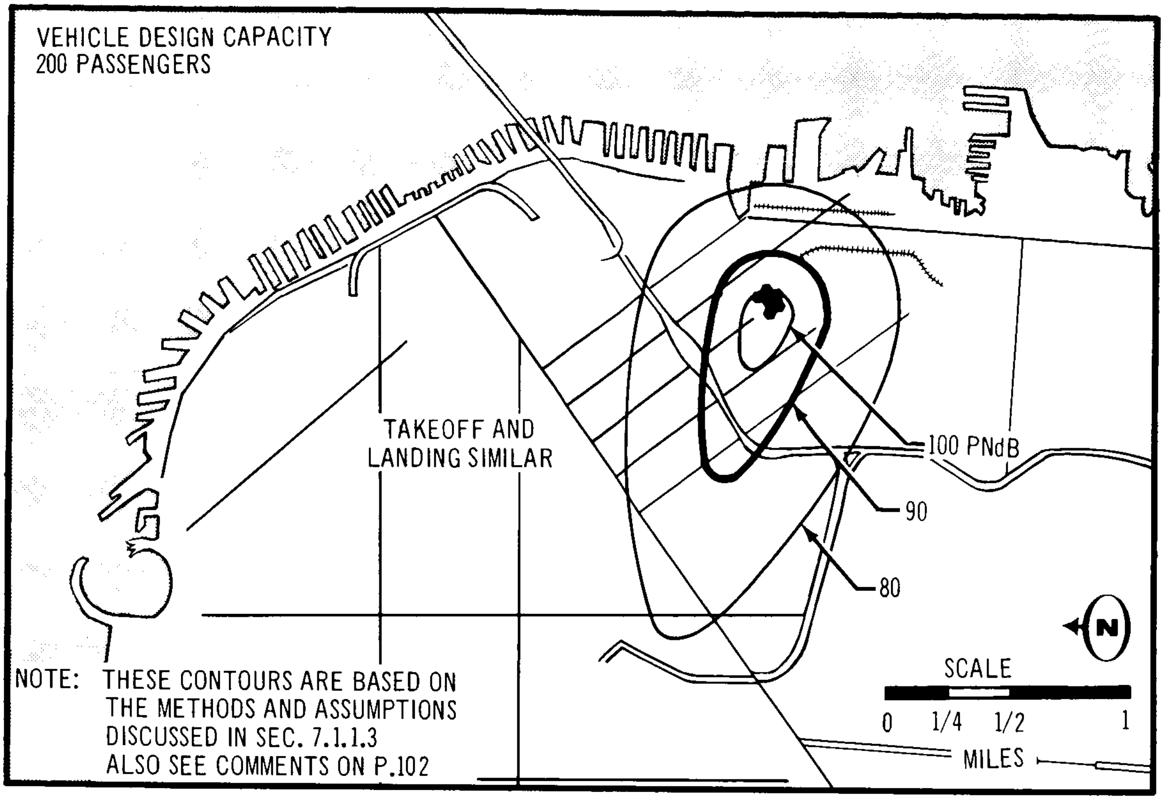


Figure 154: Tilt-Wing VTOL Noise Contours—San Francisco

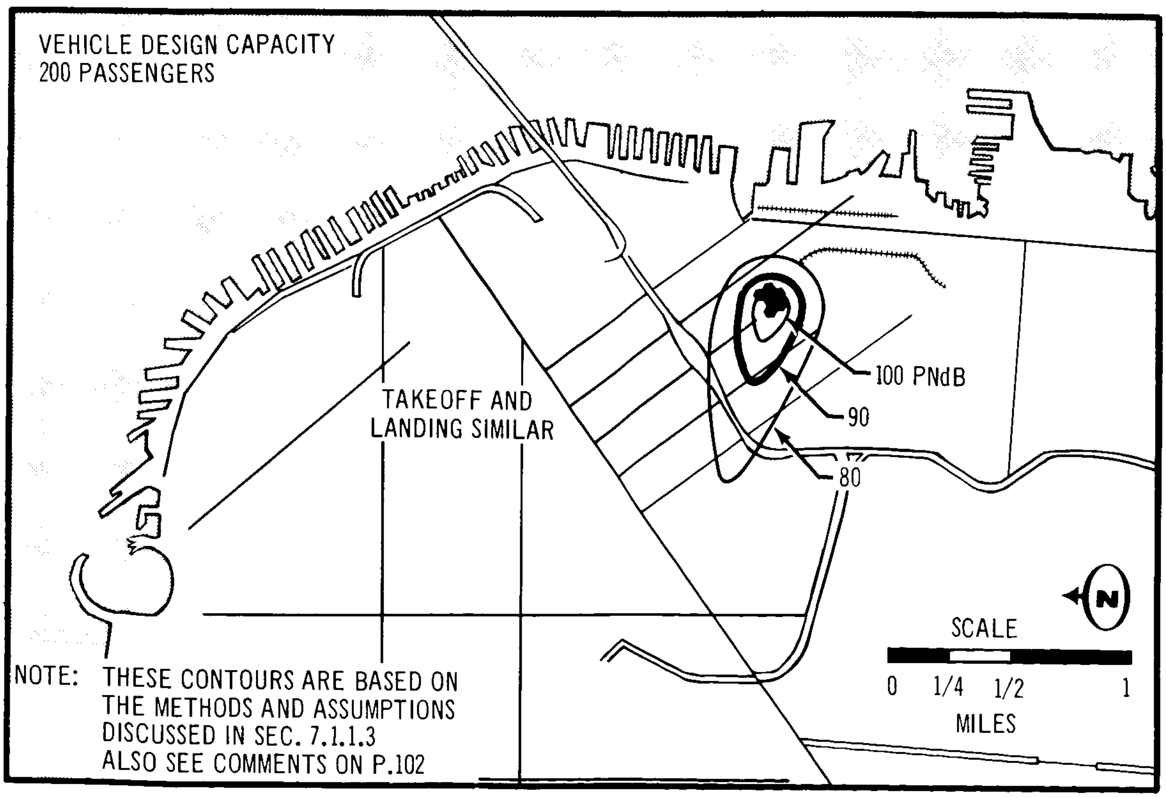


Figure 155: Folding Tilt Rotor VTOL Noise Contours—San Francisco

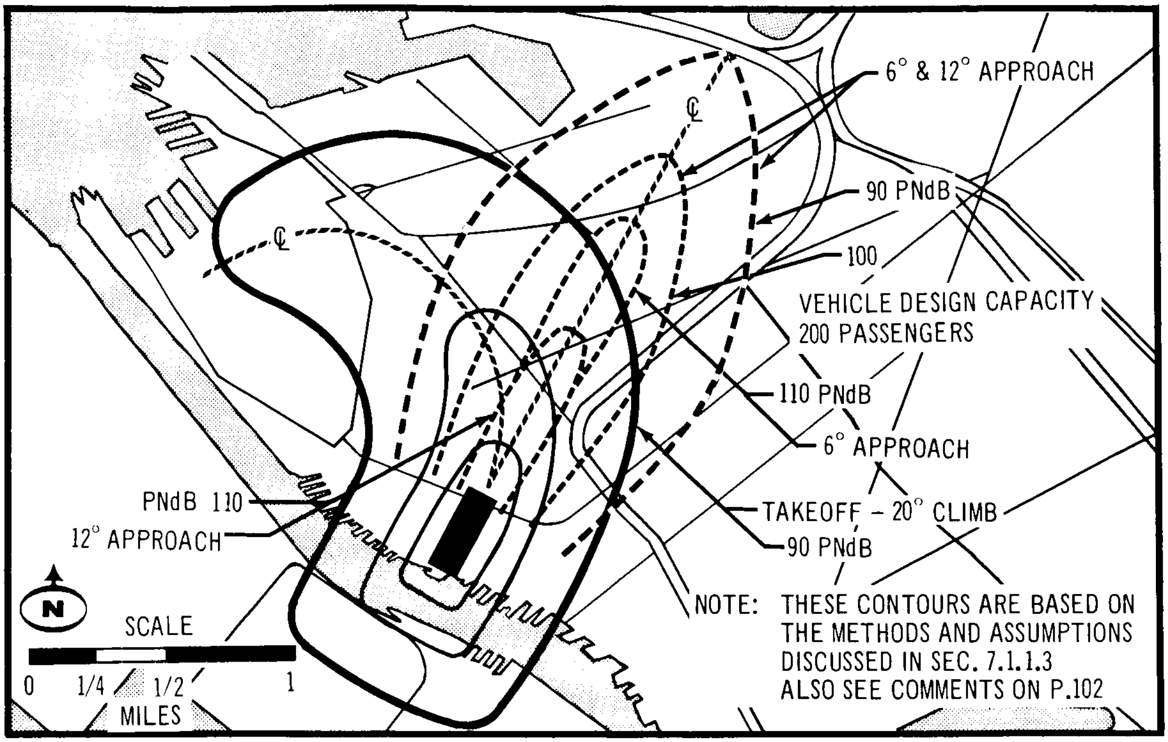


Figure 156: High-Acceleration STOL Noise Contours—San Francisco/Oakland

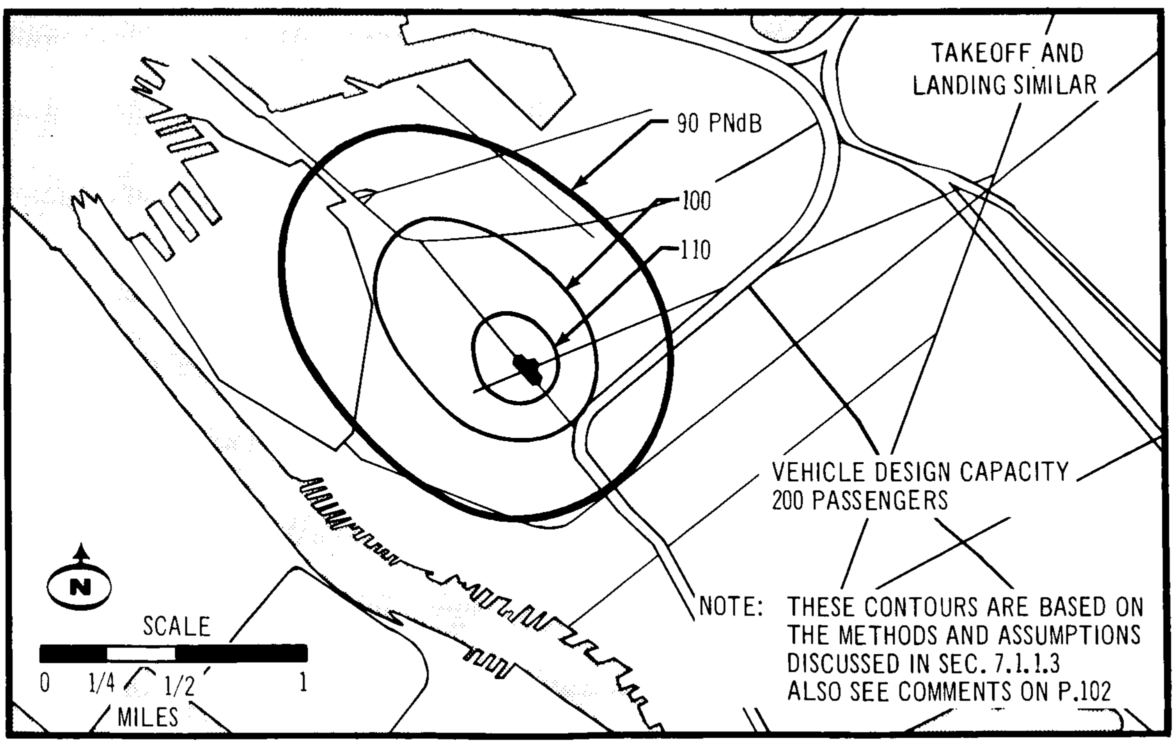


Figure 157: Jet-Lift VTOL Noise Contours—San Francisco/Oakland

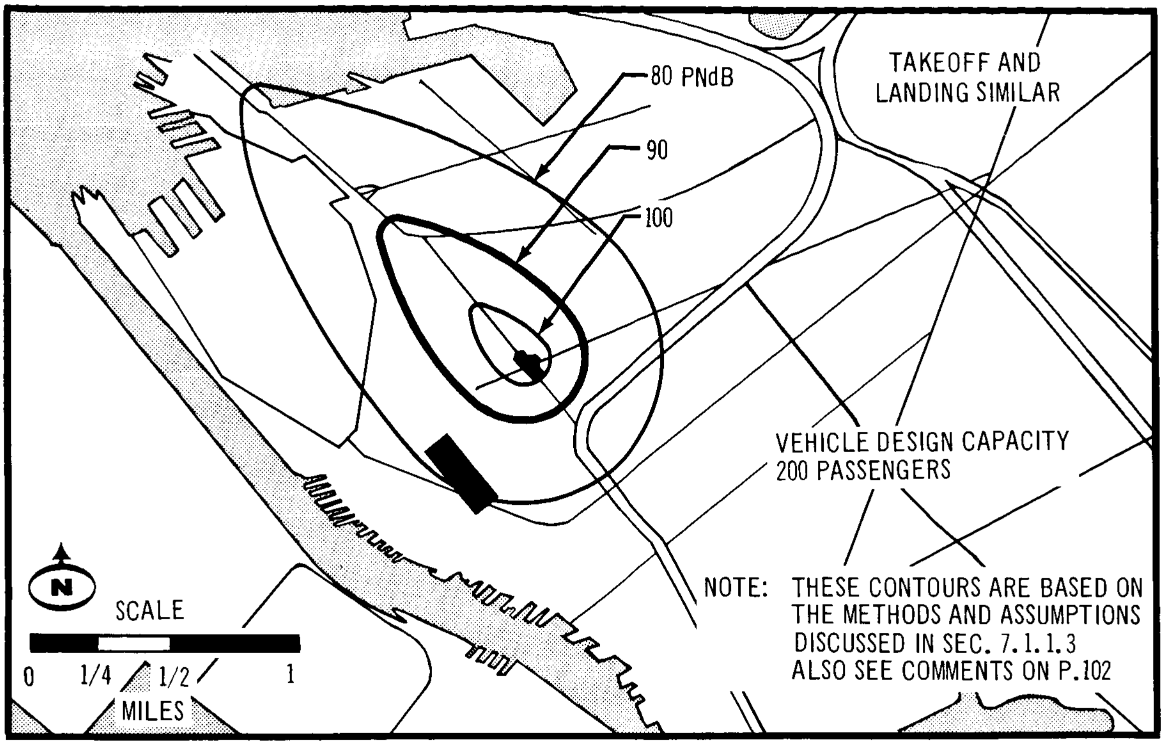


Figure 158: Tilt-Wing VTOL Noise Contours—San Francisco/Oakland

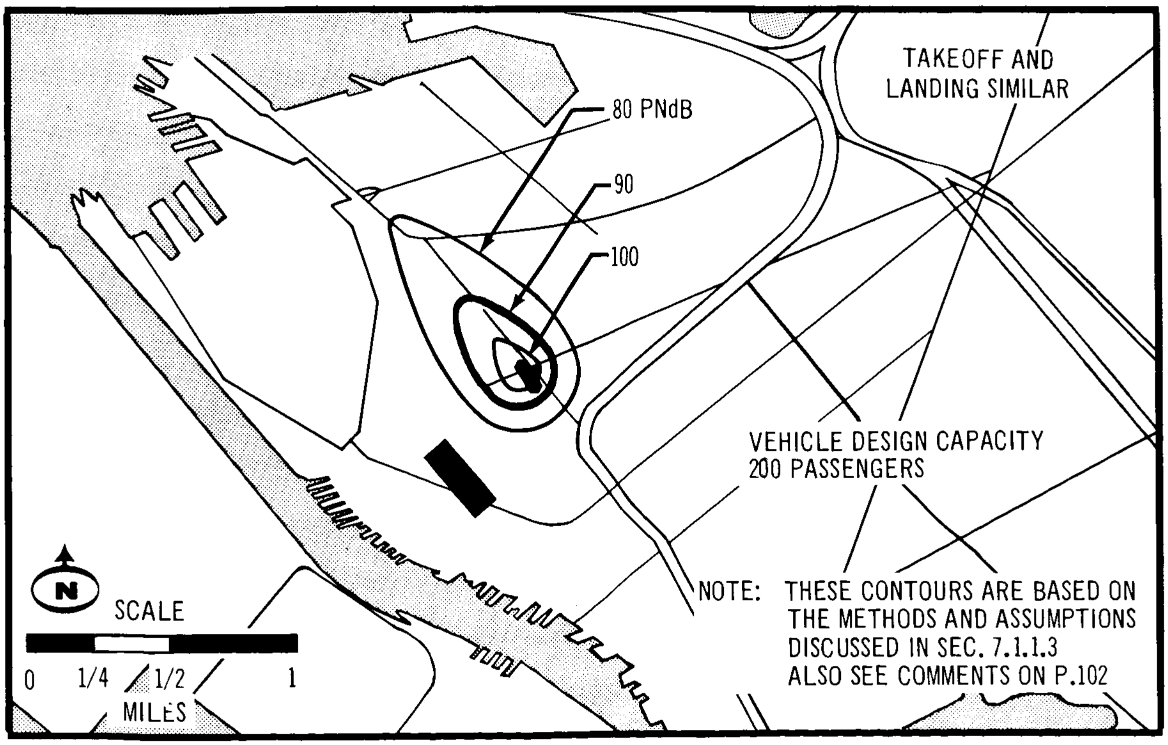


Figure 159: Folding Tilt Rotor VTOL Noise Contours—San Francisco/Oakland

appear to be satisfactory from an operational viewpoint, steep approach angles of 12° or greater are probably not. The distance from touchdown that the 90-PNdB contour extends along the approach track is not a function of altitude but of engine power setting, as shown in fig. 139.

Similar curves for the high lift STOL are shown in figs. 135 and 136. Here the climbout angle is limited by maximum power, and is a function of flap setting. The profile shown in fig. 138 includes an acceleration after takeoff to 109 kn and climbout at this airspeed.

Steep approach angles are more difficult to achieve with the high-lift STOL because of the high minimum power setting (65%) associated with blown flaps. Operational approach angles on the order of 6° or 8° are probably the maximum attainable.

In the review and assessment of the final location of possible V/STOL ports, charts were prepared showing the composite noise contours drawn on certain selected city maps. These are presented in figs. 140 through 159.

As the noise analysis in this study progressed, it became more and more evident that noise considerations should play a large part in designing the configuration, both VTOL and STOL. Figures 160 and 161 show the effect of engine bypass ratio and fan tip speed on perceived noise level. The bypass ratio of the cruise engines on all concepts as well as the lift engines on the jet lift VTOL and high acceleration STOL were set at five and design fan tip speed at 1200 fps to minimize the noise generated. This caused no penalty for the cruise engines, but incurred approximately 4% DOC increase with the bypass-ratio-5 lift engines.

Another area in which noise affected the design was the elimination of the reaction control nozzles on the fan-in-wing VTOL. The nozzles added approximately 15 PNdB to the noise contours, and were thus replaced by tip-driven control fans.

7.1.2.8 Sensitivity considerations. — Variations of some of the more important design parameters are considered here in their effect on direct operating cost. This effect in turn can be converted to a change in profit level on the system as described in sec. 6.6.1. These sensitivity studies were not made for those concepts which were shown to have significantly higher direct operating costs in the preliminary evaluation. Therefore, of the rotor type aircraft studied in the first phase (stowed rotor, helicopter, and folding tilt rotor), only the folding tilt rotor was subject to sensitivity studies.

The tilt wing was introduced into the study too late to be considered in this section; however, the results of technology tradeoffs conducted with the folding tilt rotor were considered generally applicable to the tilt wing because of the similarity in the proportional breakdown of major component weights.

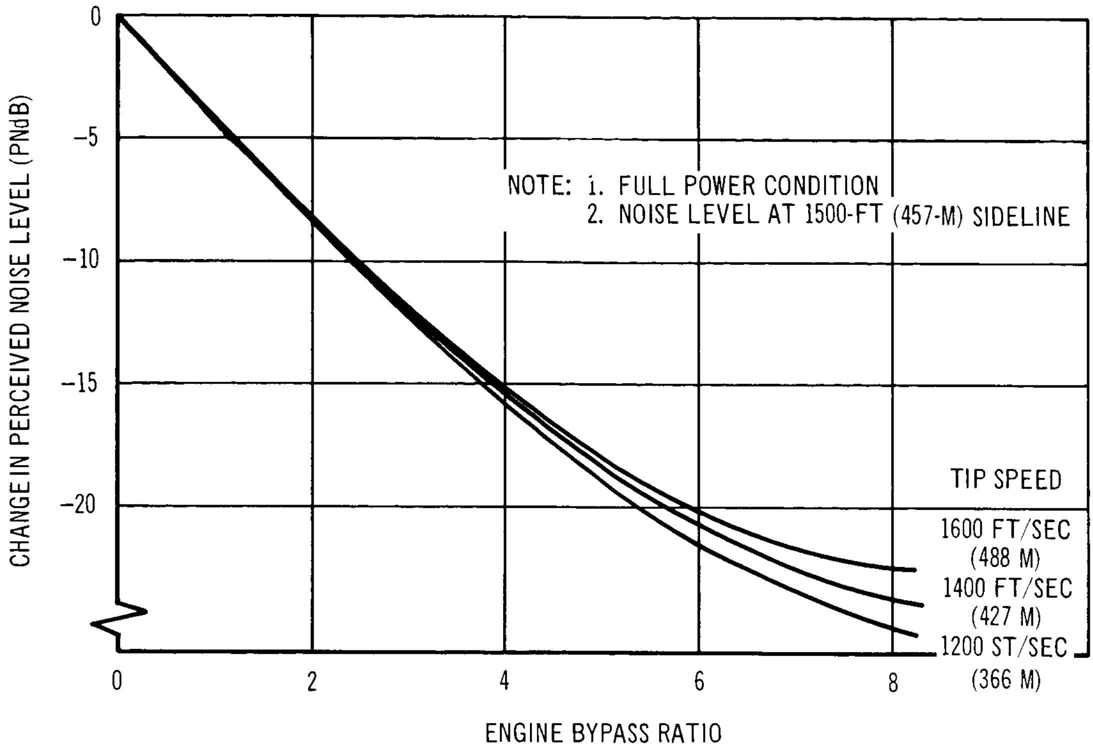


Figure 160: Effect of Tip Speed and Bypass Ratio on Perceived Noise

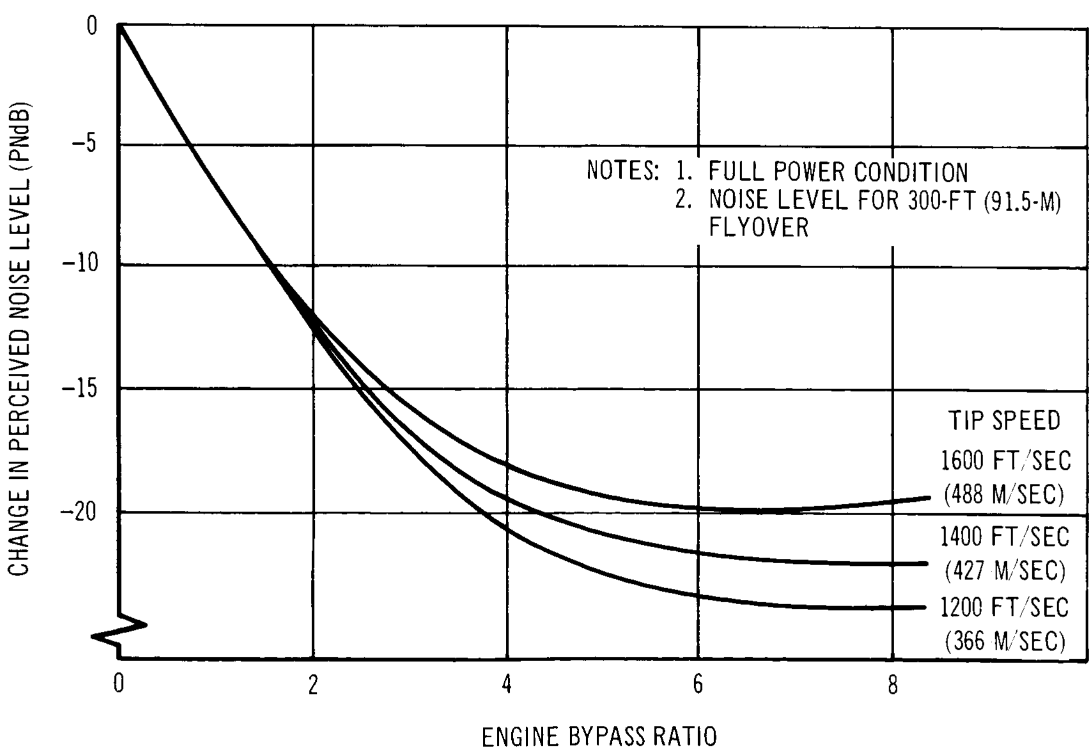


Figure 161: Effect of Tip Speed and Bypass Ratio on Perceived Noise—300-Foot Flyover

Table 11: Percent Reduction in Direct Operating Cost Due to Technology

1985 Technology						
				Weights Only		
Concept	Total	Aero Only	Engines Only	Total	Fixed Equipment	Structures
Folding Tilt Rotor	31	3.6	5.0	25.4	4.1	21.4(11.3)*
Fan-In-Wing	33	7.0	10.5	17.0	4.1	12.9(7.3)
Jet Lift	24.8	5.5	6.6	15.3	4.0	11.3(5.6)
Hi-Accel	29.2	6.1	8.0	19.5	4.0	15.5(8.5)
Hi-Lift (1650)	34	10.3	3.3	23.6	4.0	19.6(9.7)
Hi-Lift (2200)	27	7.5	3.3	16.5	4.0	12.5(6.3)
CTOL	22	5.0	2.0	14.0	3.8	10.2(5.2)

NOTE: 120 PASSENGERS
300 NMI (555 KM)

* ADVANCED TITANIUM

7.1.2.8.1 Technology: The effect on DOC of the advanced technology previously outlined is shown in table 11 for all concepts except the tilt wing. The overall effect as well as a breakdown of this effect into three major categories is included. The values shown are the increments from the all-1966 technology level to the level obtained, with one technological category at the 1985 level and the remainder at the 1966 level. The category labeled weights only (total) includes fixed equipment as well as structure weight reduction as shown. The value in parentheses in the structure column indicates the DOC reduction from the 1966 level available with the use of advanced titanium structure in place of the composite material. (See section 7.1.1.4 for a discussion of advanced titanium and composite materials.) The 1985 engines category reduction is mainly due to the reduced weight of the engines. The category marked 1985 Aero includes the combined effects of the reduction in skin friction, increase in critical Mach number and increase in placard speed.

The 1966 airplanes used here for comparison are not completely optimized airplanes. The general characteristics are similar to the 1985 configurations, i.e., W/S, T/W, wing sweep, aspect ratio, etc. In the case of the STOL airplanes, this results in a change in design field length. At a constant-design field length of 2200 ft (671 m), the high-lift STOL experiences approximately a 43% reduction in DOC when the 1985 technology level is used instead of the 1966 technology level. The 1985 flap technology allows the wing loading to be increased to 90 lb/ft^2 (440 kg/m^2) as compared to a wing loading of 60 lb/ft^2 (294 kg/m^2) with the 1966 technology.

The advance in technology assumed in the area of structural and equipment weights yields the largest reduction in DOC, up to twice the reduction of aerodynamics and propulsion combined. The reduction is greatest for those concepts with the highest ratio of structure to gross weight.

The advance in aerodynamic technology results in reduced flight time for all concepts, this reduced time accounting for the major portion of the reduction in DOC. Included in this section of advanced technology is the increase in placard speed allowed by gust alleviation on some concepts. The STOL airplanes with low wing loadings gain the most here.

The reduction in DOC due to engine technology is roughly proportional to overall installed thrust. The fan-in-wing airplane has an additional increment included here accounting for the change in type of powerplant, from a tip driven fan to a concentric fan.

These results do not change significantly at shorter ranges.

7.1.2.8.2 Maneuver time: Maneuver times, both air and ground, have a large effect on the DOC of all concepts. The effect is approximately inversely proportional to range so that the shorter ranges are affected more as shown in figs. 162 and 163. For the CTOL airplane at 150 nmi (278 km), each minute of ground maneuver time increases the DOC approximately 3 percent and each minute of air maneuver time increases the DOC approximately 5 percent. At the design range of 300 nmi (555 km) this effect is reduced to 1-1/2 percent and 3 percent, respectively. The helicopter is the only concept that varies significantly from these percentages and shows about half this amount. For the VTOL concepts, the additional item of hover time must be considered.

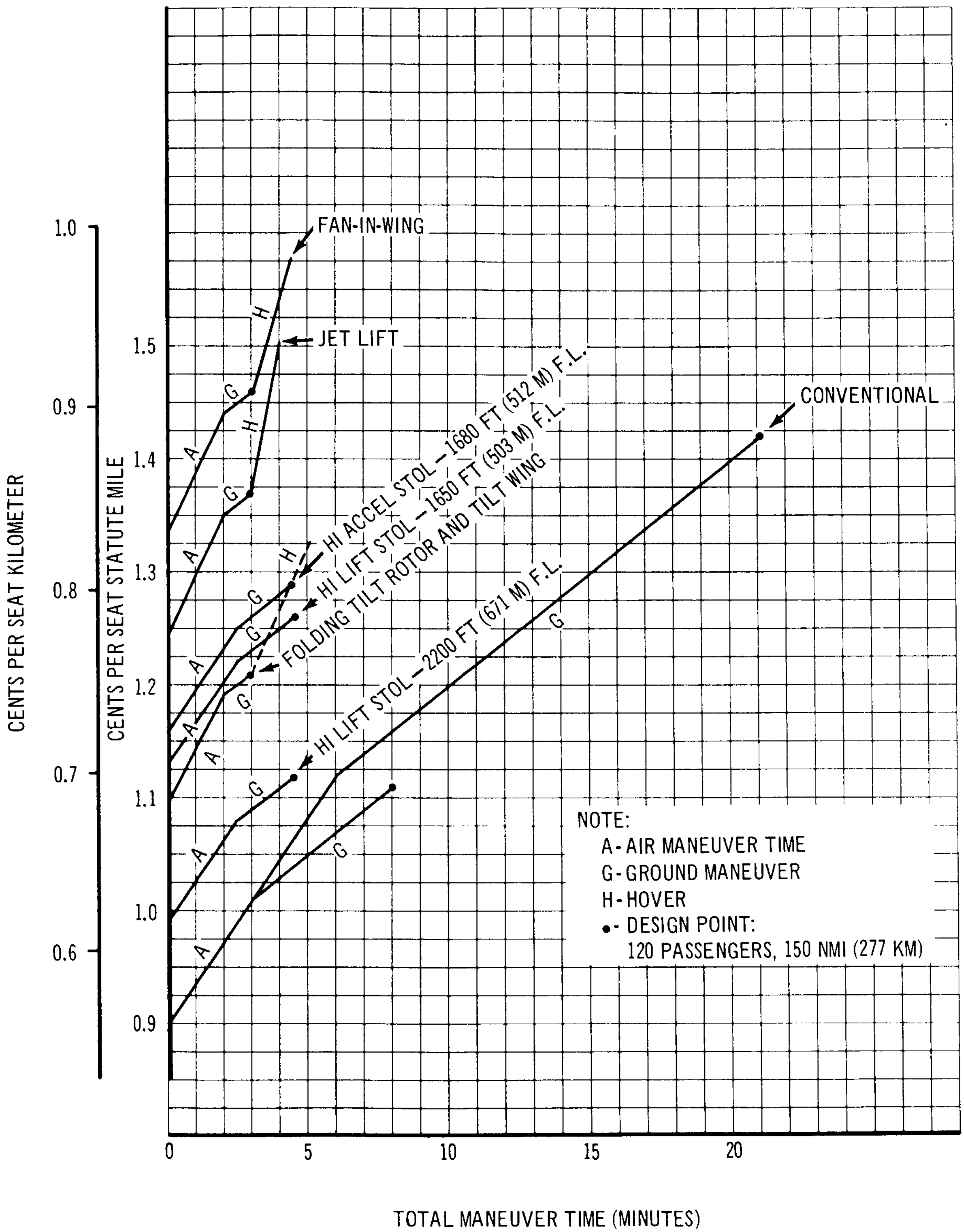


Figure 162: Effect of Maneuvering Time on Direct Operating Cost—150-nmi Range

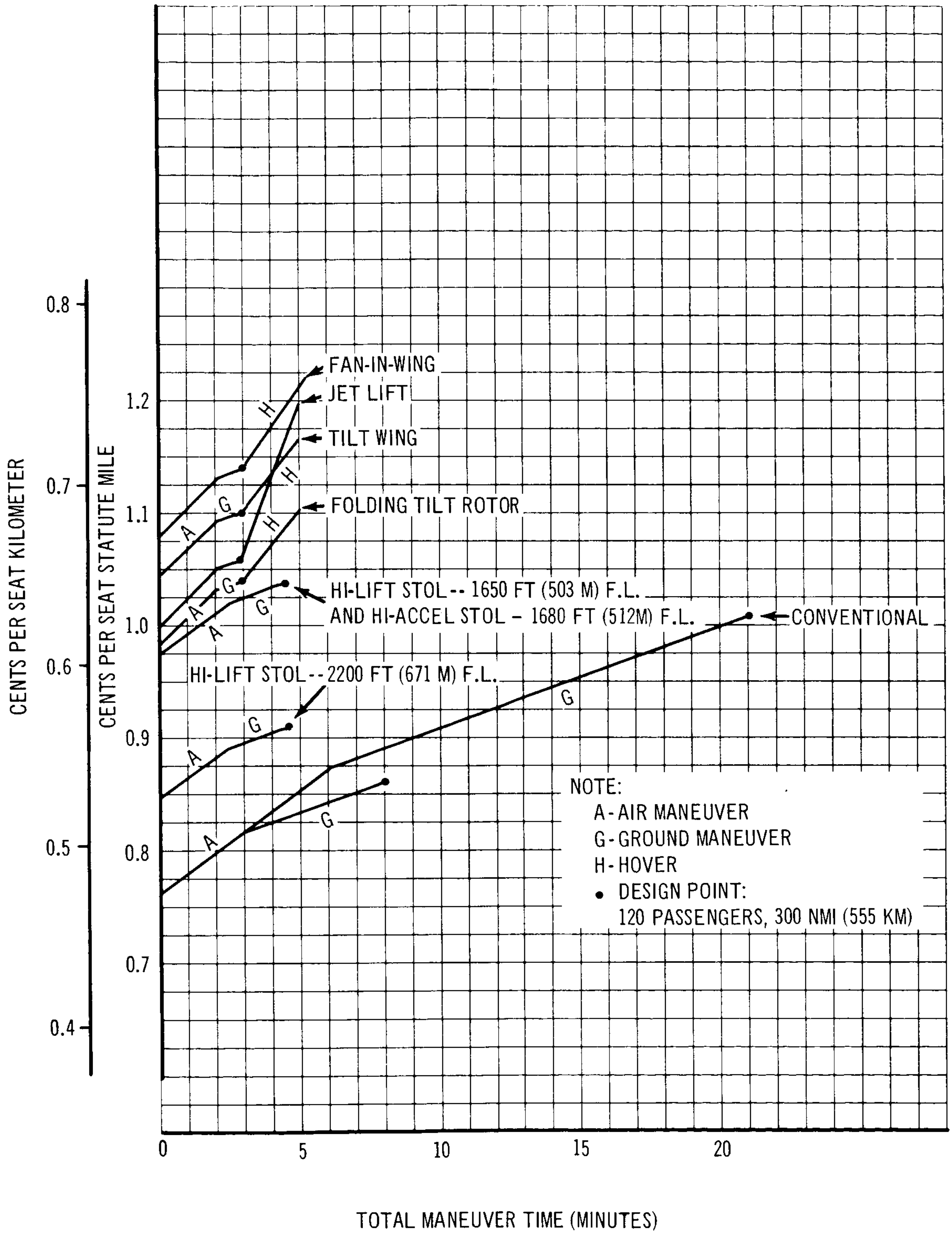


Figure 163: Effect of Maneuvering Time on Direct Operating Cost—300-nmi Range

7.1.2.8.3 Hover time and weather considerations: A review was conducted of selected weather data from the U.S. Department of Commerce Weather Bureau for the three geographical regions of interest in this study. Data are presented in these sources that summarize the hourly observations of ceiling and visibility on a percentage frequency basis with respect to height and distance. The period of data collection was generally for 5 years.

Conclusions drawn from this data are as follows:

Northeast	% of Time	Ceiling (ft)
Average (long-term basis)	0.5	0
	0.5-1.25	100-200
	1.5-2.75	300-400
	3.5-6	500-900
With worst short-term peaks (monthly basis)	2	0
	4	100-200
	6	300-400
	9	500-900
West Coast		
Average (long-term basis)	0.5-1	0
	1 -1.8	100-200
	1.2-3	300-400
	1.5-9	500-900
With worst short-term peaks (monthly basis)	3	0
	4	100-200
	6	300-400
	20	500-900
Gulf Coast		
Average (long-term basis)	0.25-0.66	0
	0.5 -2.5	100-200
	1 -2.5	300-400
	2 -5	500-900
With worst short-term peaks (monthly basis)	2	0
	6	100-200
	6	300-400
	11	500-900

If the assumption is made that 100% reliable all weather zero-zero landing aid capability is provided at all VTOL terminals, then theoretically there is no requirement for hover that would be associated with the weather limitations.

If, on the other hand, various minimum ceiling conditions are exercised, a relationship between landing equipment requirement, frequency of ceiling occurrence, and potential hover time can be obtained.

At a rate of descent of 500 ft/min (2.5 mps) it is postulated that if the ceiling is above 300 ft (91.5 m), no hover time is required. There is sufficient time after breakout for the pilot to assess the situation and initiate and carry out corrective action associated with a possible 100-ft (30 m) miss distance.

Hence, if the ceiling is 300 ft (91.5 m) or less, it is assumed that 1/2 minute of hover time is required after breakout to make final landing corrections.

It is concluded that if zero-zero capability is not provided and that no other landing pad associated problem is preventing immediate landing, it may be necessary to hover for 1/2 minute for possible 1-1/4% to 2% of the total yearly operations depending on the region under consideration.

The effect of hover time on DOC shows a more pronounced variation between concepts. Rotor concepts show little or no increase in DOC over straight air maneuver time. The fan-in-wing, however, shows a minute of hover time as costing 40% more than a minute of air maneuver time. And the corresponding figure for the jet lift is 100%.

7.1.2.8.4 Fuel reserves: The diversion distance used in obtaining fuel reserves has only a small effect on the DOC of the airplanes studied. An increase in diversion distance of 100 nmi (185 km) increases the DOC by 0.5% to 1%. This effect is small because of the efficient cruise performance obtained at long range cruise speeds. The extra fuel reserves, carried for an additional 100-nmi (185 km) diversion distance requirement, amount to only 1% to 1-1/2% of the gross weight.

7.1.2.8.5 Maximum versus minimum takeoff weight: For operations at ranges shorter than the design range, the effect of takeoff weight on DOC is negligible. Figure 164 shows this effect for the fan-in-wing airplane. At the short ranges where this off-design flying is accomplished, the cruise speed is limited by the placard so that any change in flight time is due only to a change in climb performance. This change is essentially zero on all concepts. The only effect on DOC, then, is that caused by differing fuel consumption. When an airplane with a design range of 500 nmi (928 km) is operated at the very short range of 50 nmi (93 km), the gross weight can be reduced by as much as 8% if only enough fuel is carried for the 50-nmi (93 km) mission (plus reserves).

However, the corresponding drag reduction, and hence fuel flow, is less than 1%. This can be visualized in the drag polar summary, fig. 165, where at the cruise speed of 400 kn (205 m/s) EAS, 92% to 99% of the total drag is independent of the airplane weight.

7.1.2.8.6 Cruise speed and altitude: The cruise speed, altitude, and cruise engine T/W were optimized for each concept. At the longer ranges, the cruise Mach number had the greatest effect on DOC. Figure 166 shows a typical variation of DOC with cruise altitude, Mach number, and cruise T/W for a VTOL airplane where the cruise T/W can be varied without changing the overall T/W. Optimum thrust loading and cruise Mach number occur where the maximum cruise thrust limit Mach number is approximately Mach 0.01 to 0.02 above the critical Mach number. Because of the differing wing sweeps,

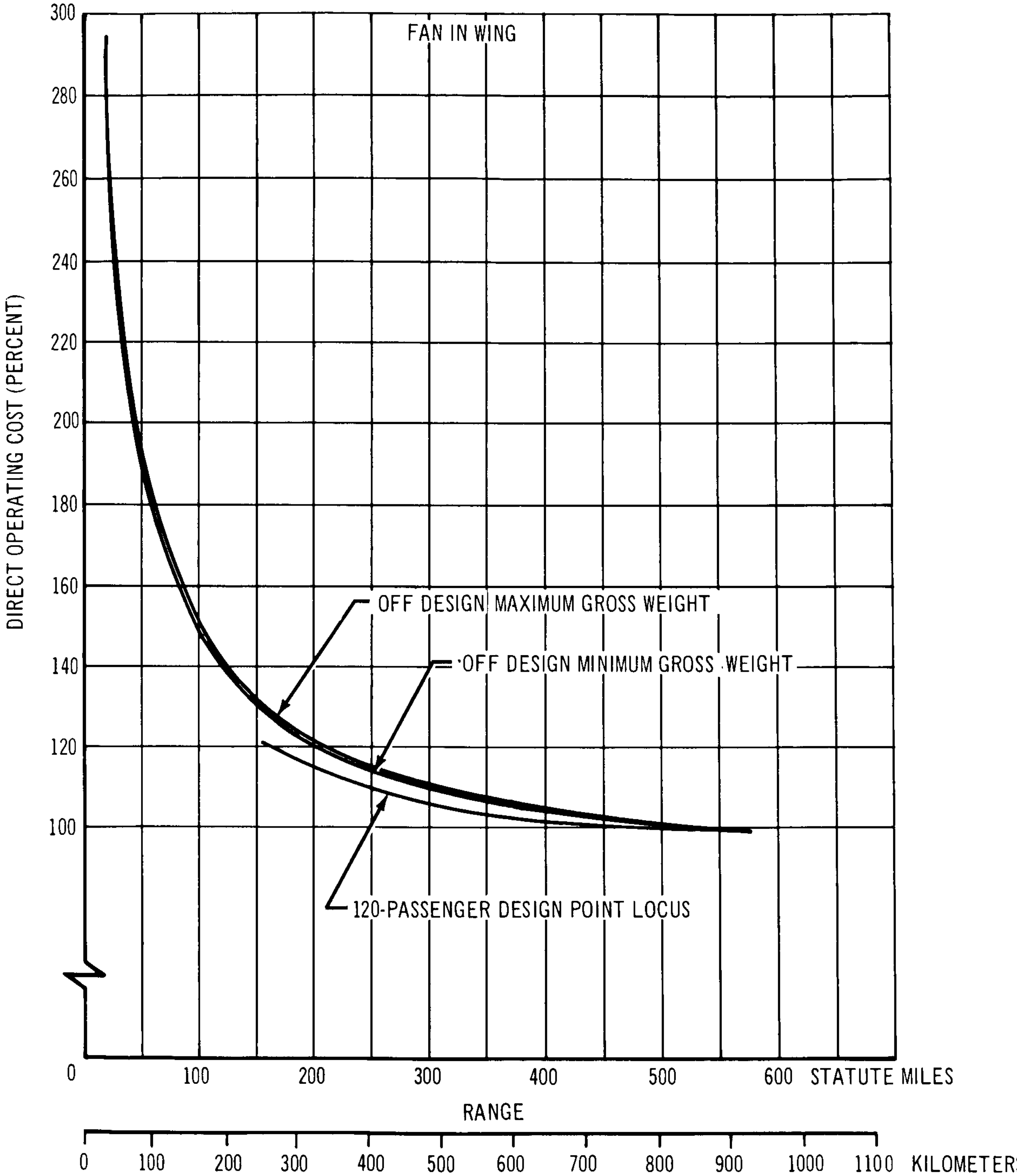


Figure 164: Effect of Gross Weight on Off-Design DOC

and therefore differing critical Mach numbers, the optimum cruise Mach varied from 0.87 for the folding tilt rotor to 0.96 for the fan-in-wing. (See sec. 7.1.2.5 for reasons for different wing sweep.) For the CTOL, the T/W is fixed by the takeoff requirement. Its minimum DOC cruise speed at the T/W for a 6000 ft (1830 m) field length is 0.90 Mach. The cruise Mach for the tilt wing is limited at 0.777 by the propeller efficiency characteristics, as shown in fig. 121.

At short ranges, the cruise speed is limited by the placard and the altitude by a balanced range condition (cruise range equals climb plus descent range). This speed/altitude relationship can be visualized in fig. 167 where the average altitudes for balanced range conditions are marked for reference. The effect of placard speed on DOC is presented in fig. 168 for the intermediate range, 150 nmi (278 km). At shorter ranges, the thrust cutoff line would allow a higher placard speed but it would be usable only at that shorter range (lower altitude), and the extra weight associated with the higher placard would be carried along (unused) at longer ranges. For this reason, the placard speed was optimized at 150 nmi which is at the low end of the high-traffic-volume city pairs considered in this study.

In addition to looking at an optimum subsonic cruise Mach number, boomless supersonic or transonic cruise was investigated. The configurations, as optimized for subsonic flight, have L/D's, at Mach 1.15, of 0.8 to 3. Most of the excess drag is volume wave drag and is being affected adversely by the low body fineness ratios, small wings, and engine pod locations. With reduced body cross sections and some tailoring, the cruise L/D ratio could be raised to as much as 3.5 or 4 for the 200-passenger airplanes. However, to achieve 6, which is as low as any used in subsonic cruise at 400 kn (205 m/s) EAS, complete tailoring of the configuration for transonic flight would be necessary.

In the case of transonic, transcontinental transport flying at Mach 1.2 at 45 000 ft (13 700 m), where a 20% increase in true airspeed applies to 80% or more of the mission range, it is difficult to make the aircraft competitive on a DOC basis with subsonic transports. For the short ranges being considered here of 300 to 400 nmi (556 to 742 km), the 12% increase in true airspeed, applying to only 50% or less of the mission range, does not justify economically the large compromises necessary to obtain it.

7.1.2.8.7 Field length: Takeoff and landing performance on all concepts was based on a sea level 89° F (305° K) day. Variations in field length for the CTOL and STOL's was considered.

Takeoff performance of the conventional airplane is based on a generalized curve of takeoff performance taken from the performance of existing airplanes, and modified slightly for secondary effects of ground-roll drag and rotation rates. With the flap technology assumed and an approach speed requirement of 124 knots (638 m/s, the maximum wing loading becomes 105 lb/ft^2(513 kg/m^2). Takeoff field lengths are varied by changes in thrust loading. Landing field lengths were not critical for takeoff distances of 4000 ft (1220 m) or more.

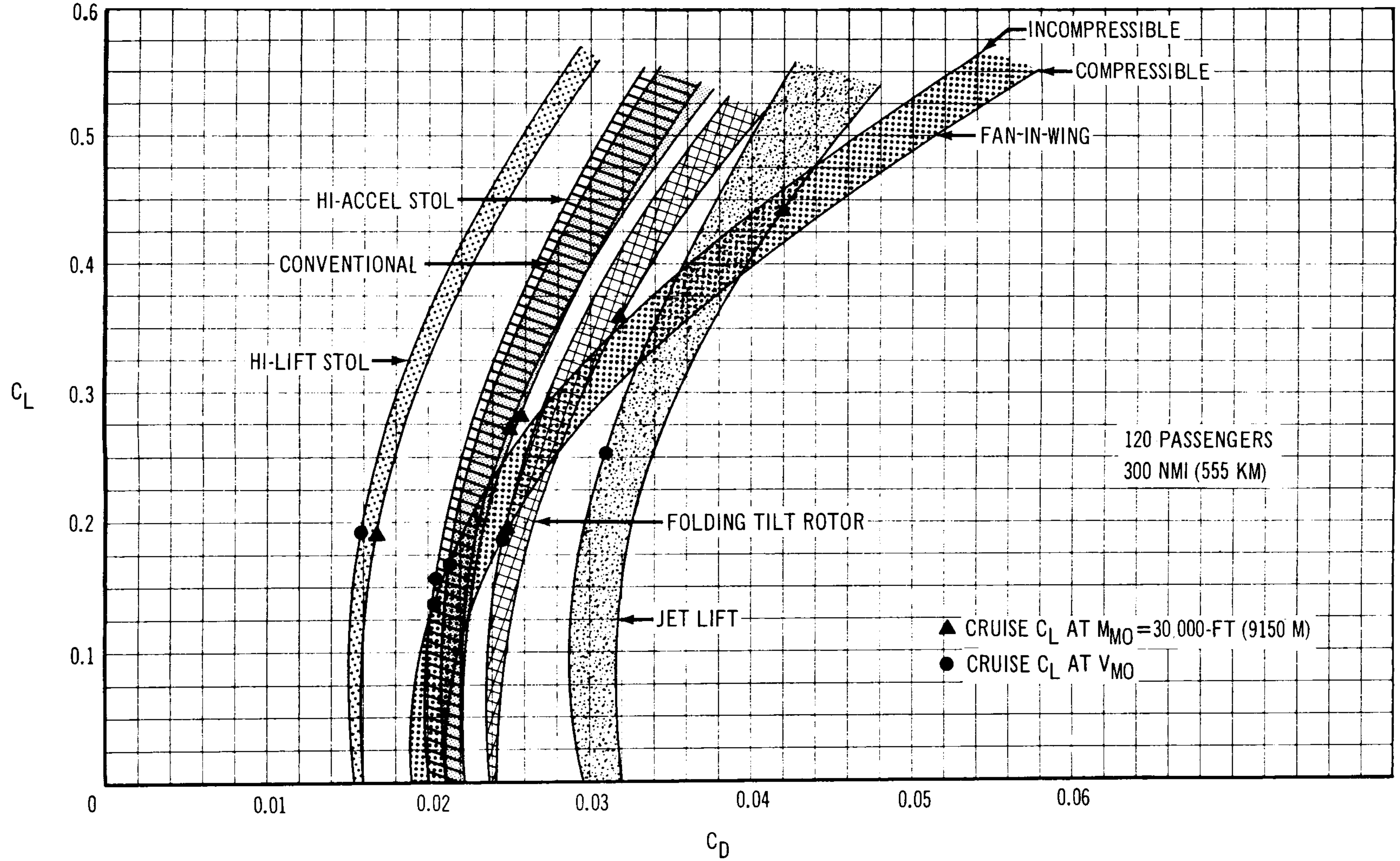


Figure 165: Drag Polars—All Concepts

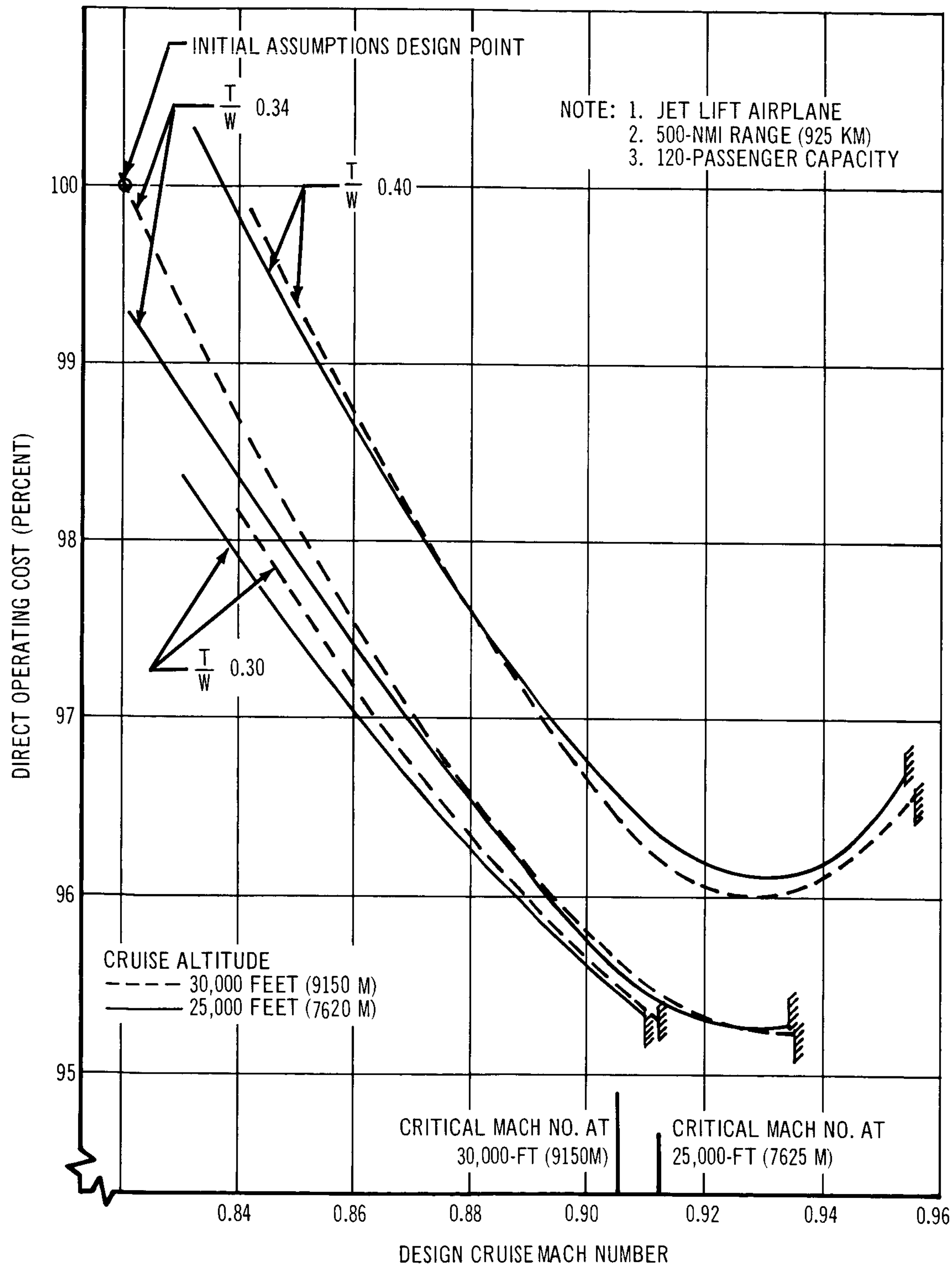


Figure 166: Design Cruise Mach Number

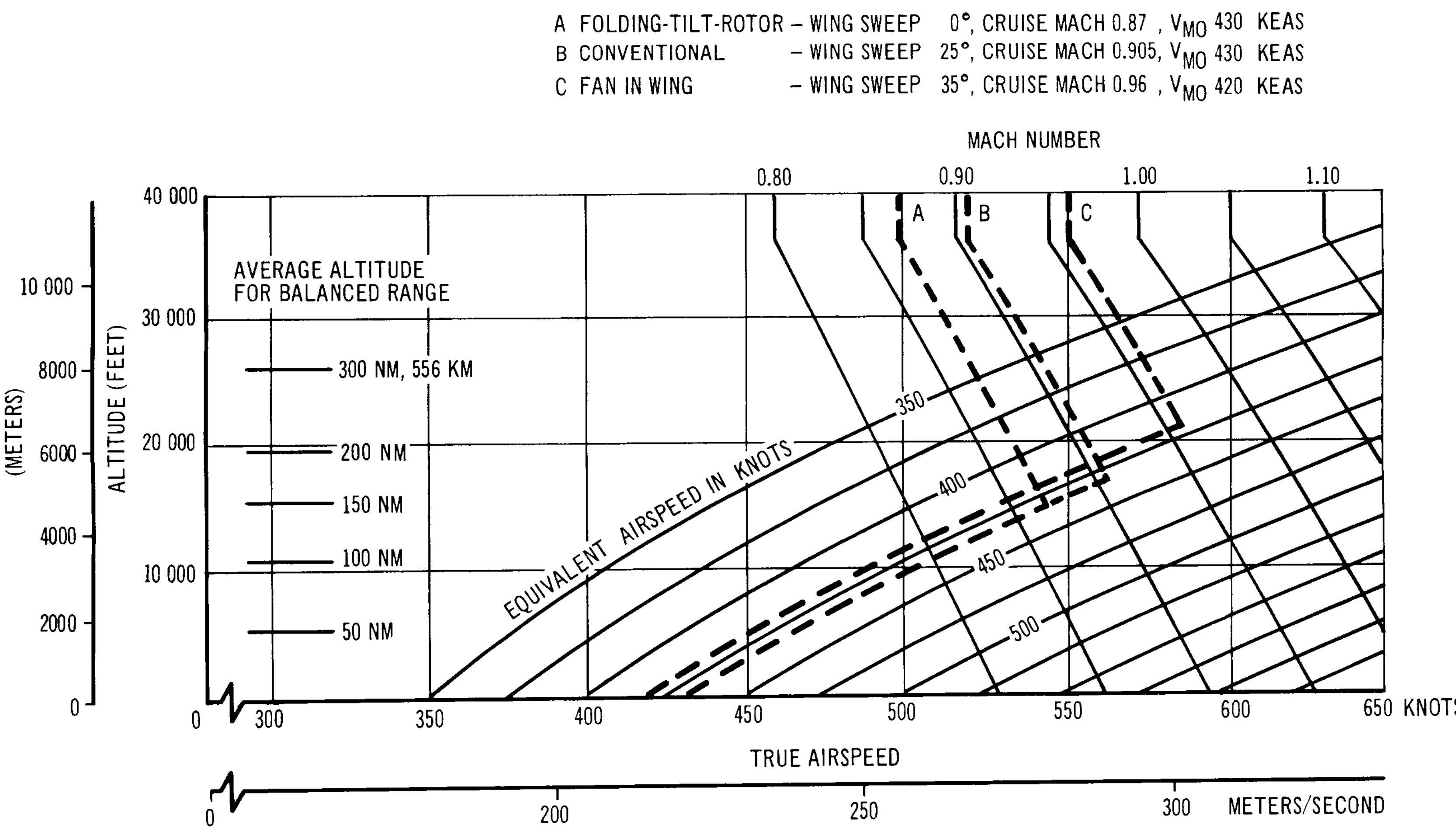


Figure 167: Speed/Altitude Relationship

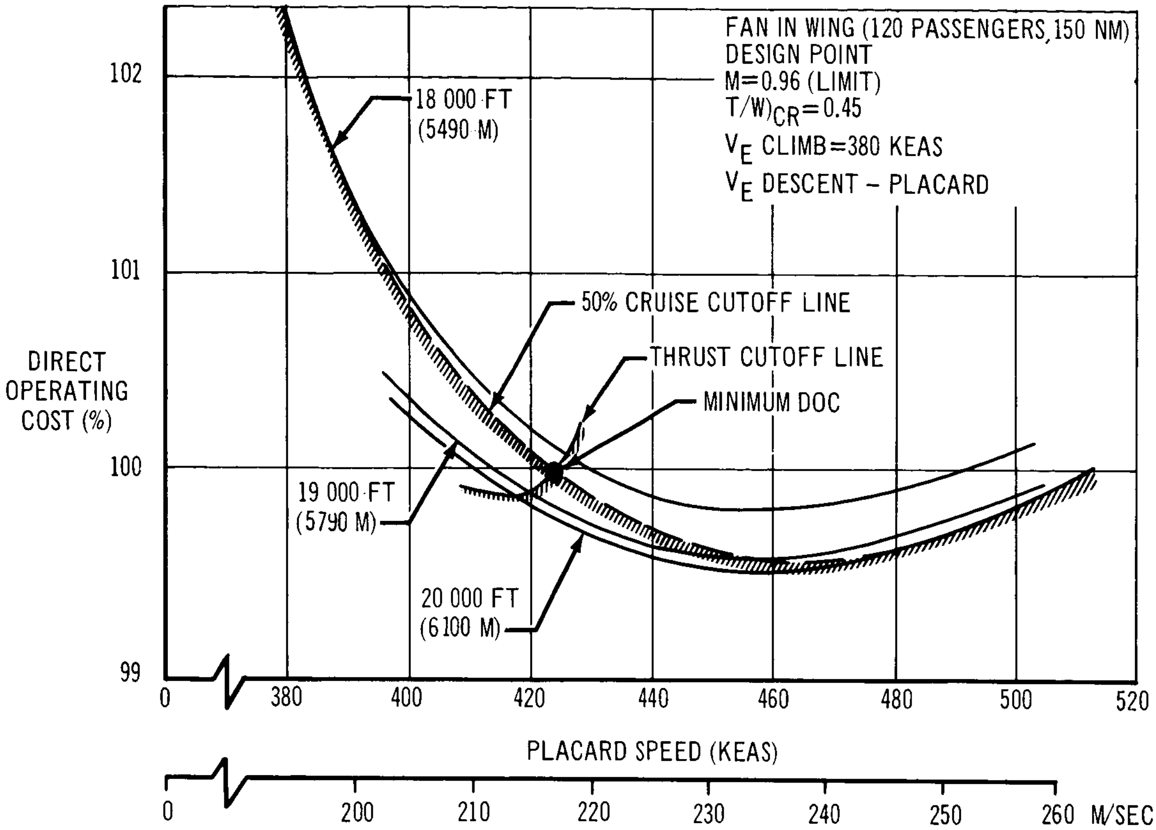


Figure 168: Optimum Placard Speed

The design field length for the CTOL was established after a review of fig. 169 where the effect of design field length on DOC is shown, and table 12, in which is shown the longest available field length in each city of the three systems. The value of 6000 ft (1830 m) was selected.

For this design, the thrust loading required for a 6000-ft (1830 m) field length equaled the thrust loading required for a Mach 0.9 cruise. Designing to a longer field (lower T/W) reduces the optimum cruise Mach number and designing to a shorter field leaves the airplane overpowered in cruise and causes a small increase in DOC as shown in fig. 169.

The high acceleration STOL achieves its field performance by supporting part of the airplane weight with lift engines, and by vectoring a large portion of the lift engine thrust horizontally for high deceleration or acceleration. In the shorter field being considered, 3500 ft (1070 m) or less, the takeoff is not critical and variable field performance is based on landing capability.

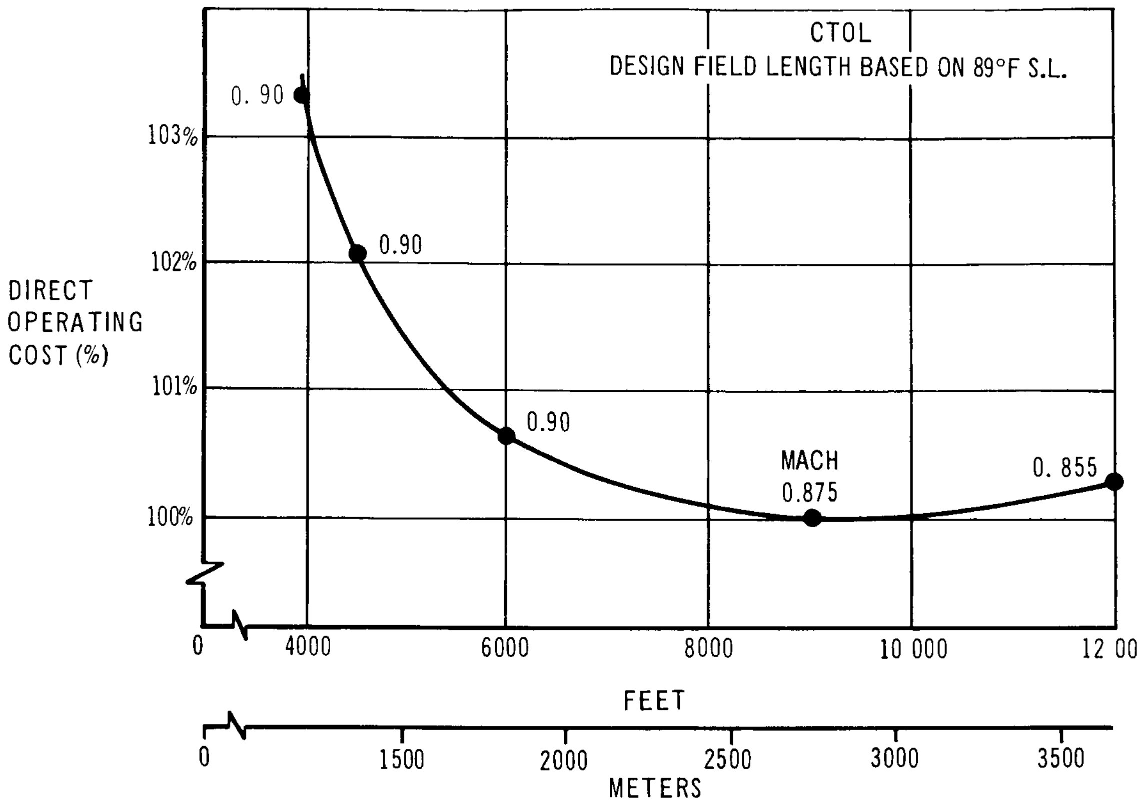


Figure 169: Effect of Design Field Length on DOC—CTOL Design

With a fixed approach angle, and a maximum deceleration rate allowed of 1/2 g, the landing field length is approximately proportional to the approach speed. The approach speed with no lift engines is 103 knots (53 m/s), which gives a landing field approximately 3500 ft. long. With a hot day, and a T/W of 0.75 for the lift engines, the approach speed is reduced to 73 knots (37.5 m/s), which gives a field 1680 ft (512 m) long. This speed includes a margin above the minimum control speed obtained with aerodynamic controls. The effect of field length on the DOC of the Hi-Acc STOL can be seen in fig. 170.

Variations in field length for the Hi-Lift STOL are achieved by varying the wing loading. At a wing loading of 60 lb/ft^2 (294 kg/m^2), the approach speed is 68 kn (35 mps) and the landing field length is 1650 ft (503 m). (See sec. 7.1.2.3 for a discussion of landing field length rules.) At a wing loading of 90 lb/ft^2 (440 kg/m^2), the approach speed is up to 83 kn (42.6 mps) and the field length is 2200 ft (671 m). To make the takeoff field length equal the landing field length, the T/W ratio required is 0.37.

Referring again to fig. 170, the effect of the very low wing loadings on DOC is seen. The weight of the wing goes up quite rapidly with decreasing wing loading, so that with the price of the airplane based on a constant number of dollars per pound of empty weight, the price of the airplane increases rapidly with decreasing wing loading. For this reason, wing loadings of less than 60 lb/ft^2 were not considered competitive.

Table 12: Longest Runway Length—Selected Cities

City	Airport Name	1966 No. of runways	1966 Longest runway (feet)
NORTHEAST			
Albany	Albany County	3	5 000
Buffalo	Greater Buffalo International	4	8 100
Boston	Logan International	4	10 023
Hartford	Bradley	3	9 525
New York/Newark	LaGuardia	2	7 000
	Newark	2	7 000
Norfolk	Municipal	3	6 000
Philadelphia	Philadelphia International	4	9 491
Providence	Green	4	5 466
Richmond	Byrd Field	3	9 000
Rochester	Rochester-Monroe County	5	7 000
Syracuse	Hancock	3	9 005
Washington, D.C.	National	4	6 870
	Friendship International	3	9 450
WEST COAST			
Las Vegas	McCarran Field	3	12 545
Los Angeles	Los Angeles International	4	12 090
	Long Beach	5	10 000
	Van Nuys	2	8 000
	Ontario	2	9 982
Phoenix	Sky Harbor	2	10 300
Reno	Reno	3	9 000
Sacramento	Sacramento	3	6 003
San Diego	San Diego International	2	8 700
San Francisco	Oakland International	4	10 000
	San Jose	2	7 787
Tucson	Tucson International	4	12 000
GULF COAST AND FLORIDA			
Atlanta	Atlanta	4	10 000
Birmingham	Birmingham	3	9 997
Dallas/Ft. Worth	Greater Southwest	3	9 000
Houston	Hobby Field	4	7 600
Jacksonville	Imeson	3	7 959
Miami	Miami International	4	10 500
New Orleans	New Orleans International-Moissant	3	9 225
Orlando	Heandon	4	6 000
San Antonio	San Antonio International	3	8 500
Tampa	Tampa International	4	8 700

Conversion Factor for International Units (feet x 0.305 = meters)

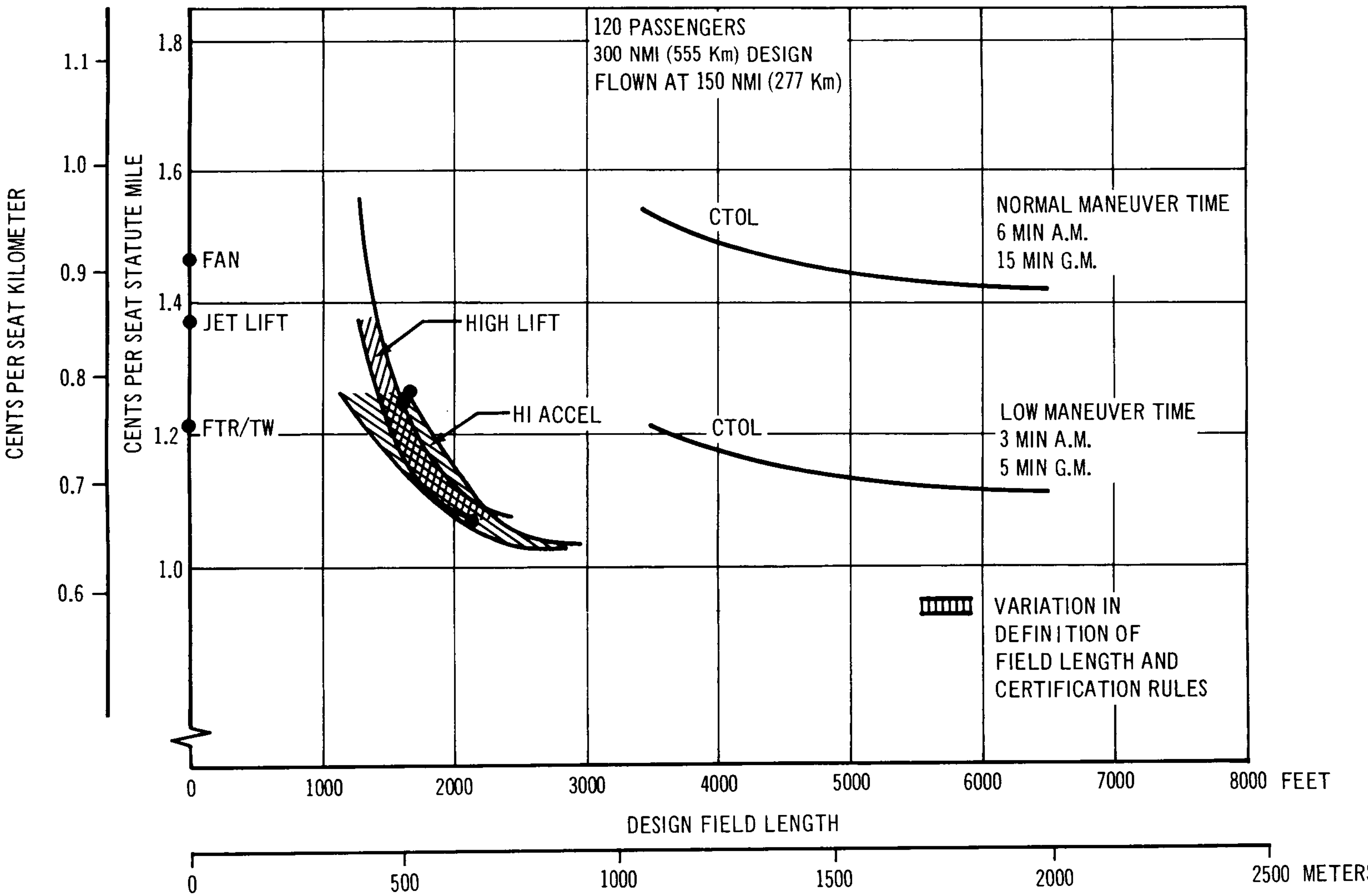


Figure 170: Effect of Design Field Length on DOC—STOL and CTOL Concepts

It is assumed that the "downtown" STOL port will require only one runway. A requirement greater than this significantly affects the ability to place the terminal in a convenient downtown location. It can be shown that high-wing loading airplanes with approach speeds of the order of 124 kn (63.8 m/s) can operate successfully in cross winds of 35 kn (18 m/s), while the recent McDonnell Report E390 indicates that low-wing-loading airplanes with lower approach speeds can successfully negotiate 30 kn (15.4 m/s) cross-winds.

While it is recognized that the STOL strips would have to be oriented in each city with the least probability of cross-wind, the sketches depicting the possible location of STOL ports included in this report have not had the benefit of this analysis. It has, however, been assumed that a suitable orientation can be determined for a single runway in each city so that operations will not be restricted by cross-winds.

7.1.2.8.8 Control requirements: The control requirements listed in the ground rules were used in the design of all VTOL concepts. Figure 171 for the jet-lift VTOL aircraft shows the effect of varying these requirements from 20% to 200% of the original values. The penalty in DOC for doubling the control requirement is approximately 4% here and is similar for other sizes and concepts. The bleed and burn reaction control system with turbocompressors shows the lowest DOC; however, when the lift and cruise engines are modulated for control, the DOC is only slightly higher in the high-capacity airplanes, and shows better for the low capacities.

For the jet lift, a modulated engine control system is used as it eliminates the need for an additional system. In addition, the reaction control nozzles were ruled out as being too noisy. In the jet lift configuration, the engines are sized by the engine-out condition, using half of the all-engine control requirement. The simultaneous use of only 80% on the primary axis and 40% on the remaining axes on this configuration would reduce the DOC by 0.5%.

The fan-in-wing concept requires a separate control system: the lift fans are not separated enough to give good control moments.

Varying the control power requirements for STOL aircraft is not as easily converted to a DOC. The primary variables are the size and complexity of the roll control devices on the wings, as the horizaontal and vertical tails are sized by stability requirements. The trade would be smaller than fig. 171 indicates for the VTOL, however.

7.1.2.8.9 Noise: The first calculation of noise contours showed the jet lift aircraft with pure jet lift engines to be some 15 PNdB higher in noise level than the other VTOL concepts. The noise level for a mixed engine concept such as this is based primarily on the noisiest of the engine types used. To lower the overall noise level, the lift engines were replaced with turbofan engines of the same bypass ratio as the cruise engines. The penalty in DOC for this change is approximately 4%.

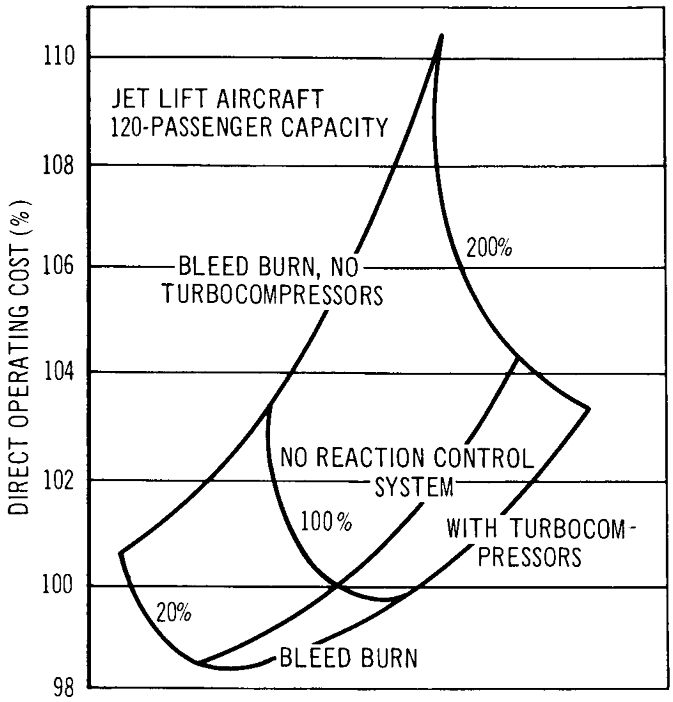


Figure 171: Effect of Size and Type of Control System on DOC

In the case of the fan-in-wing airplane, the fans are several PNdB quieter than the cruise engines so that the cruise engine noise is predominant.

A bypass ratio of 5 was chosen for the cruise engines to minimize the noise generated as shown in figs. 160 and 161. In these curves, the general downward trend of noise level with increasing bypass ratio begins to flatten off as a function of the relative improvements in noise control between jet noise and inlet or discrete frequency noise. The relationship shown is that assumed for the 1985 period. The development of an efficient jet noise silencer could change this relationship significantly.

Figure 98 shows the effect of cruise engine bypass ratio on the airplane gross weight. The tip speed of 1200 ft/sec (366 m/s) is used here and requires a substantial (but obtainable) improvement in engine design over the current engines.

With these design features fixed, some additional reduction in noise is obtained with variations from the ideal (minimum DOC) mission profile. Figures 172 and 173 show the DOC penalty associated with noise reductions available from varying amounts of initial vertical climb (and final vertical descent) for the VTOL concepts. The DOC penalty with these same initial vertical climbs for the folding-tilt rotor are about one third of that shown for the jet lift and the fan-in-wing.

The climbing turns after takeoff for the STOL concepts incur a penalty of 1.5% on DOC at a range of 200 mi (322 km).

7.1.2.8.10 Discussion of results: As a result of the sensitivity studies performed about the base configurations of each concept, certain operating and design factors appear to have more impact than others on the direct operating costs of the vehicle.

At the shorter ranges of 200 to 300 nmi (370 to 555 km) — i.e., those of high traffic density — variations in maneuver time had the greatest effect on DOC. It has been shown (figs. 162 and 163) that the DOC of a CTOL vehicle can be affected substantially by changes in aircraft maneuver time. It is conceivable that between now and 1985, future terminal and runway design, air traffic control procedures, and airplane operational procedures will bring about reduced ground and air maneuver times. Thus, it was considered essential to include in the analysis two versions of a CTOL concept: a normal maneuver time airplane (6 minutes air and 15 minutes ground) and a low maneuver time airplane (3 minutes air and 5 minutes ground).

It is apparent from fig. 170 that very short field lengths are difficult to attain economically. The high-acceleration STOL is limited by a horizontal deceleration level of 0.5 g, considered a maximum for passenger confort in normal operation, and approach angle for operational consideration. The hi-lift STOL rapidly becemes unattractive economically as the field length goes below that attainable with a wing loading of 60 lb/ft^2 (294 kg/m^2). Here also the field length is somewhat higher because of the relatively low approach angles.

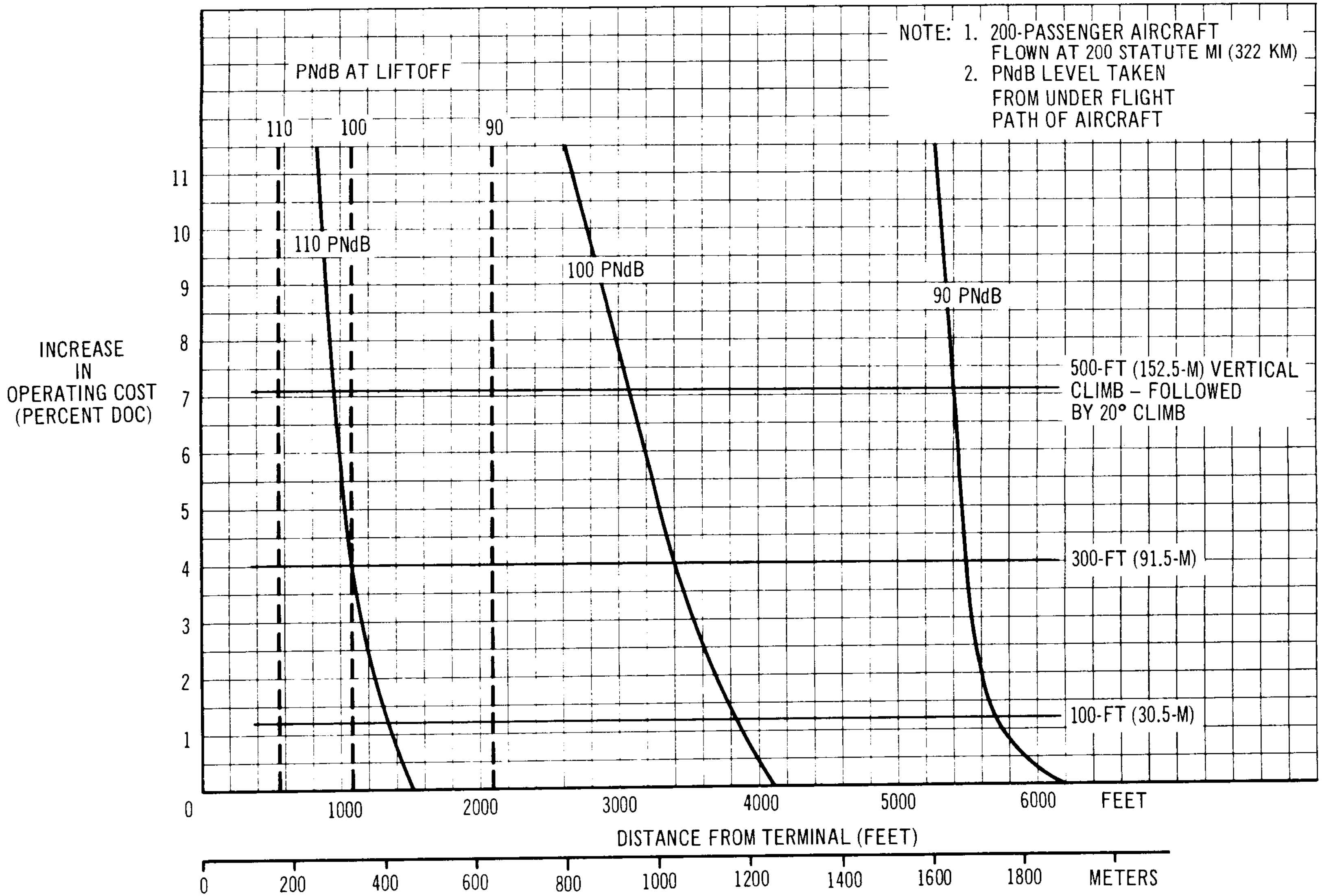


Figure 172: Operating Cost Penalty Noise Abatement Maneuvers—Jet Lift

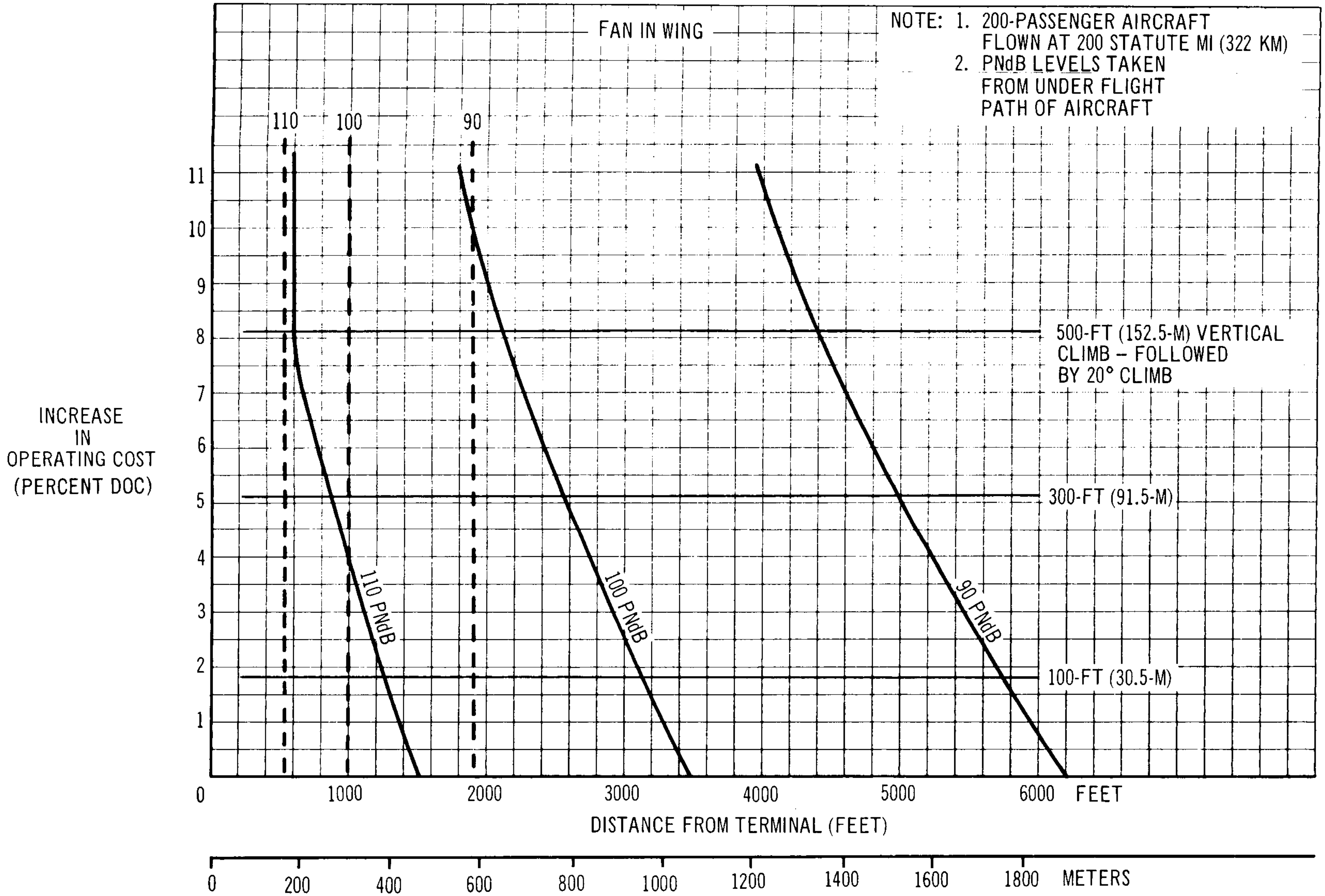


Figure 173: Operating Cost Penalty Noise Abatement Maneuvers—Fan in Wing